ORBIT MANEUVER FOR RESPONSIVE COVERAGE USING ELECTRIC PROPULSION

THESIS

Timothy S. Hall, Captain, USAF

AFIT/GSS/ENY/10-M04

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GSS/ENY/10-M04

ORBIT MANEUVER FOR RESPONSIVE COVERAGE USING ELECTRIC PROPULSION

THESIS

Presented to the Faculty

Department of Aeronautics & Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science (Space Systems)

Timothy S. Hall, BS, MA

Captain, USAF

March 2010

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT/GSS/ENY/10-M04

ORBIT MANEUVER FOR RESPONSIVE COVERAGE USING ELECTRIC PROPULSION

Timothy S. Hall, BS, MA

Captain, USAF

Approved:

Dr. Richard G. Cobb (Chairman)	12 MAR 2010 date
Dr. Jonathan T. Black (Member)	12 MAR 2010 date
Douglas D. Decker, Lt Col, USAF (Member)	15 MAR 2010 date

AFIT/GSS/ENY/10-M04

Abstract

The use of continuous electric propulsion to manipulate a satellite's orbit offers significant potential for enhancing coverage of a target in ways not previously considered. Elliptical orbits utilizing a very low perigee can facilitate access to the surface and atmosphere of the Earth at sub-ionosphere altitudes while counteracting atmospheric drag forces using continuous electric propulsion. Additionally, in-plane and out-of-plane manipulation of both circular and elliptical orbits can allow for passage of a satellite over a target at a given time.

Sustained low perigee orbit was modeled with an initial perigee altitude of 100 km and various apogee altitudes to derive a range of apogee altitudes that could sustain the orbit. Operation was demonstrated for current as well as future thruster capabilities.

To evaluate opportunities for a scheduled access, circular and various elliptical orbits were modeled using continuous thrust. It was found that electric propulsion was capable of improving potential temporal access of a target to 30% for circular orbits and nearly 70% for elliptical orbits. Only minimal improvements in coverage were found using manipulation of the right ascension of the ascending node.

Recommendations include further modeling of low perigee orbits and the effects of atmospheric variation at solar extremes on mission lifetime. Derivation of optimal thrust duration and angle could greatly enhance the performance of the thruster and warrants continued research. Finally, the use of responsive maneuver operationally will require development of a scheduling algorithm to plan passage over a given target at a given time.

Table of Contents

Page

List of Figures

List of Tables

ORBIT MANEUVER FOR RESPONSIVE COVERAGE USING ELECTRIC PROPULSION

1. Introduction

1.1 Background

1.1.1. Taskable Space Assets and Customizable Orbits

Trends in space operations are trending towards greater flexibility. Assets are under great demand and old operating concepts no longer capture the needs of the end user. The Department of Defense has acknowledged the need for responsive space systems. According to Lt Col Robert Newberry, USAF: “The opportunities for advanced spaceflight training, concept of operations (CONOPS) and tactics, techniques, and procedures (TTP) development, space range, and experimentation merit serious consideration” [1]. His advocacy of a new concept of operations is well heeded and has enormous potential.

Opportunity exists for scientific, commercial, government, and military use of taskable space assets. Adaptive communications networks, environmental monitoring, as well as traditional intelligence, surveillance, and reconnaissance missions are only a few of the many possible missions that could utilize a maneuverable asset. In order to exploit these capabilities, a departure from traditional paradigms in satellite operations is required.

Satellite operations have historically been limited to large scale impulsive maneuvers for orbit establishment and smaller impulsive and continuous maneuvers to maintain the orbit. However, there is potential to make each satellite more responsive to

the users' demands. In some cases, it is desirable for the satellite to pass a designated location at a given time. Using current and planned electric thruster technologies, it is possible to manipulate the orbit to achieve not only an access between the satellite and a target but to do so at a designated time.

1.1.2. Spacecraft Flight vs. Maneuver

Space flight is typically very inflexible. Missions are designed around specialized orbits to fulfill specific missions. However, this concept has taken a great deal of flexibility away from space-based systems. Actual maneuver of spacecraft has been limited to station keeping operations and constellation optimization movements. However, advances in low weight continuous thrust engines opens up the possibility for tactically-maneuverable satellites. Orbits can be shaped to create unpredictability in the orbit and achieve a space-based presence over a target at any given time. Additionally, the satellite can be placed in opportune locations at favorable times maximizing the benefit of the space-based asset.

1.1.3. Continuous Propulsion

One key to a flexible satellite mission profile is the use of continuous thrust on spacecraft. Traditionally, the operations concept of a satellite mission minimizes maneuvers other than for necessary station keeping purposes. The ability for a spacecraft to maintain an orbit and fulfill its design mission is directly dependent upon the amount of fuel available on board the spacecraft. Unnecessary consumption of fuel to maneuver the spacecraft for short term objectives may severely constrain the life of the satellite.

Electric propulsion has become increasingly popular propulsion method as the technology and performance matures. Hall Effect thrusters have been used by the

Russians for many years to perform orbit maintenance and station keeping. Alternatively, the U.S. focused on the development of gridded ion thrusters. While many systems already benefit from electric propulsion technologies for traditional purposes, advances in both technologies make orbital maneuvers practical [2].

1.2 Research Objectives

This research evaluates multiple orbital schemes and maneuvers using electric propulsion to determine the feasibility of using low-thrust continuous propulsion for orbital maneuvers. The nominal thruster designs chosen represent a range that covers current as well as near term thruster capability. Each of the nominal thruster capabilities was iteratively compared for the following scenarios.

Highly-elliptical orbits are known for the extended coverage provided at apogee where the satellite spends the greatest part of the orbital period. The former Soviet Union took advantage of this unique fact by devising a specialized highly-elliptical orbit known as the Molniya orbit to place communications satellites over their far northern latitudes where geosynchronous orbits were poorly suited. However, this analysis considers an alternative potential. For missions requiring extremely low pass over the Earth's surface, an elliptical orbit may prove useful for achieving such an objective. By using a high apogee altitude, a perigee altitude below the ionosphere may be possible. Furthermore, the orbit may be maintained using continuous thrust to counter the significant drag forces encountered at low altitude. This analysis defines a range of potential apogee altitudes where this orbital scheme would be successful based upon current and future continuous thrust capabilities.

Additionally, continuous thrust offers the potential to maneuver a satellite within its orbit. While there are other benefits to such flexibility, this analysis will consider the use of maneuvers to manipulate the temporal coverage of a single target by a single satellite. In-plane maneuver by altering the orbit eccentricity as well as out-of-plane maneuver to alter the right ascension of the ascending node (RAAN) is considered. This analysis defines the time available for coverage of a single target from various eccentricity and inclination combinations using current and future continuous thrust capabilities to alter the eccentricity and RAAN of the orbit.

The single greatest limiting factor to spacecraft maneuver is fuel usage. Therefore, for the previously discussed combinations, fuel usage was calculated and compared to represent the potential fuel costs for each continuous thrust maneuver.

1.3 Assumptions and Limitations

The design of this research is limited in the number and type of variables that can be considered. The overall analysis is based upon computer simulation using Analytical Graphic Inc's Satellite Took Kit software suite. As with any model, there is uncertainty that will inevitably prevent perfect simulation of behavior. However, it is assumed that the overall data collected from the model is representative of typical circumstances.

For orbital determination and maneuver, STK's High Precision Orbit Propagator (HPOP) was chosen to simulate the environment. According to STK, HPOP is effective at modeling atmospheric altitudes from the lower atmosphere and higher. Furthermore, the propagator incorporates variation in the motion of the Earth and the Moon. Additionally, the spacecraft state is computed using integrated equations of motion based

upon the initial spacecraft position and velocity. Drag and mass characteristics of the spacecraft are incorporated into the analysis.

There are a wide variety of propulsion methods available to choose from. However, several nominal thrusters based upon current, near-term, and long-term projected performance are considered to demonstrate near and far term potential for near Earth orbit manipulation using electric propulsion. Electric propulsion is not currently designed for responsive maneuver. The vast majority of electric thrusters are designed for orbit maintenance and deep space or interplanetary travel. Thruster and power systems would likely need to be modified or redesigned for near Earth use. Eclipse of the satellite, thruster duty cycle, and spacecraft attitude requirements would all affect thruster configurations.

Power is the limiting factor affecting electric propulsion performance. Current systems, in low Earth orbit typically can generate from 1 kW to 5 kW of power. Achieving power above these ranges would require extensive solar arrays which would degrade the maneuverability and stability of the satellite. In the long term, unconventional power sources such as nuclear generated and beamed power may offer significant gains, but that capability is still theoretical at best. For this analysis, conventional solar power capabilities were used to derive a nominal spacecraft design.

Finally, maneuver of the spacecraft will be limited to two schemes. For the very low perigee and the temporal coverage analysis, continuous thrust from perigee to apogee is used to alter the orbit eccentricity and ultimately, the orbital period. Additionally, for the temporal coverage analysis, thrust directed normally to the trajectory is used to evaluate the potential acceleration and deceleration of ascending node regression. These

orbital schemes will serve as a proof-of-concept which can be expanded upon in subsequent research. Complex maneuvers and thrust angles will not be evaluated.

With the research problem defined, Chapter 2 will review relevant existing research. To derive the capabilities of various thruster technologies, the development and performance of various thrusters is discussed. Furthermore, existing research concerning similar orbital maneuver is discussed. Chapter 3 develops the methodology used in the research. Chapter 4 discusses the results of the analysis. Finally, Chapter 5 will identify the conclusions and recommendations for further research.

2. Literature Review

2.1 Introduction

Both continuous electric propulsion and low perigee orbits have been researched previously. However, the research for electric propulsion has been largely dedicated to traditional station-keeping applications and more recently to deep space exploratory missions. Low perigee orbits have been studied for interplanetary scientific missions. Additionally, low perigee orbits have been a part of at least one Earth orbiting mission. Use of electric propulsion to facilitate low perigee orbit maintenance and maneuver has not as of yet been formally studied or documented.

2.2 Thruster Technology

To realistically develop a responsive satellite that is capable of achieving a reasonable design lifetime, electric propulsion is one way of achieving such a goal. Electrical thrusters offer considerable weight savings, are highly efficient when compared to conventional combustion-based thrusters, and are highly reliable. Thruster development spans the entire range of technological readiness. Some of the technology is quite mature with large amounts of actual flight performance data. Conversely, there are several theoretical concepts that may offer significant near and long term advances.

While there are a wide variety of electric propulsion systems currently in use, this analysis only considers several of the most common systems. Operational systems typically fall into one of three categories: Hall Effect Thrusters (HETs), Gridded Ion Thrusters (GITs), and Magneto-Plasma Dynamic Thrusters (MPDTs)[3]. These three types of thrusters represent the technologies with the greatest maturity and where the greatest near term gains in performance are likely to occur.

2.2.1. *Hall-Effect Thrusters*

Hall-Effect Thrusters were developed by the United States and the Soviet Union simultaneously in the 1950s and 1960s. The United States abandoned development of HETs choosing to base subsequent spacecraft on chemical propulsion methods. However, the Soviet Union persisted in electrical propulsion and eventually was able to achieve a great deal of success using HETs for station keeping purposes. This technology, however, could also be used for spacecraft maneuver. Hall Effect Thrusters generate a magnetic field between a central anode ring and an outer cathode ring that traps electrons. At the anode, a gas propellant is injected and ionized. The positive ions are, in turn, attracted to the negative electron field and accelerated out of the thruster.

NASA has primarily led the way in advanced electric propulsion. This is likely due to the necessities of interplanetary and deep space travel. The high specific impulse (ISP) achieved with electronic propulsion is far more attractive for this type of travel than the use of burdensome and inefficient chemical propulsion methods.

NASA has developed two different systems specifically for space exploration. Dankanich and Polsgrove have investigated the mission benefits of the NASA Solar electric propulsion Technology Application Readiness (NSTAR) program, the NASA Evolutionary Xenon Thruster (NEXT) program, the High Voltage Hall Accelerator (HiVAC) thruster, and the commercially produced Aerojet BPT-4000 Hall Thruster. The NSTAR and NEXT systems will be discussed later in this document. As their names imply, the HiVAC and BPT-400 thrusters are Hall-Effect thrusters[4].

NASA has developed a Hall-Effect thruster designated the High Voltage Hall Accelerator (HiVAC) for Discovery Class missions. This particular design was intended

for mid-sized spacecraft applications and a longevity that is greater than is typical for HETs. With a 3.6 kW maximum input power, the thruster yields a specific impulse of 2750 sec and a thrust of 235 mN. Lifetime estimates have not yet been verified by NASA's Glenn Research Center (GRC) [4].

Similarly, Aerojet has qualified the BPT-4000 thruster and NASA GRC has verified its performance. Dankanich and Polsgrove report that this HET is designed to operate in the 3 to 4.5 kW range and at maximum power has yielded a specific impulse of 1983 sec and a thrust of 232 mN [4]. The BPT-4000 is currently qualified for GEO orbits and will be used on the Advanced EHF communications satellites [5]. The first of these satellites is scheduled for launch in 2010.

Thomas Randolph of Jet Propulsion Laboratory (JPL) has reviewed the qualification of the BPT-4000 thruster. While it is approved for commercial station-keeping applications, utility of the thruster has not been verified for long term, scientific missions. However, results from commercial applications and NASA GRC testing thus far, indicate that the BPT-4000 Thruster may be an inexpensive and attractive option. According to Randolph, there is low risk in certification of the thruster [5].

Busek Space Propulsion has developed an entire line of low and high power thrusters. The BHT-200 has flight heritage providing propulsion on the TacSat-2 mission [5]. The BHT-20K is under Air Force Research Lab sponsored development, and testing of the thruster has begun at NASA Glenn Research Center [6]. Table 2.1 shows the performance characteristics of the Busek line of thrusters.

Table 2.1 Busek Space Propulsion Thruster Specifications[7][8]

	Input Power (W)	ISP (s)	Thrust (mN)
BHT-200	200	1390	12.8
BHT-600	600	1600	41.0
BHT-1000	1000	1750	58.5
BHT-1500	1700	1820	102
BHT-8000	8000	1900	512
BHT-20K	20250	2750	1080

Hall Effect Thrusters are broadly distributed across the power spectrum. However, testing has shown that HETs are better suited to low power applications. In an evaluation of electric propulsion, the cost and performance of various thrusters was evaluated as well as the technological maturity and efficiency. NASA's Low Power Hall thruster achieved ISPs of 1500 to 2700 at input powers of 330 W to 3 kW, respectively. The throttle response was relatively linear over the range. While the low power HET offered significant lifetime advantages, the readiness of the technology is low and as of yet has no flight heritage [9].

2.2.2. Gridded Ion Thrusters

Gridded Ion Thrusters operate using a mechanism similar to HETs. However in GITs, the fuel is ionized by electron bombardment. The positive ions then diffuse towards a grid. Positive and negative grids are separated by a short distance creating an electrostatic potential between them. As the positive ions pass through the positive grid,

they are attracted towards the negative grid at a rate dependent upon the charge difference in the grids. As the positive ions pass through the negative grid, electrons are injected to neutralize the plasma.

The NASA Solar electric propulsion Technology Application Readiness thruster led the way for U.S. development of GIT technology [10]. The NSTAR thruster has a successfully demonstrated flight heritage on the Deep Space I and Dawn missions. The thruster has a thrust of 94 mN and an ISP of 3100 s at 2.3 kW of input power [4].

NASA's Evolutionary Xenon Thruster has been under development by NASA as a long term replacement ion propulsion system for high power missions. The NEXT thruster is a typical dual grid xenon fueled thruster. Long term testing of the thruster by NASA GRC has shown that the thruster operating over its designed power input range of 500 W to 6.9 kW yielded thrust s of 26 to 237 mN and ISPs of 1360 s to 4170 s respectively. Herman and Patterson were able to demonstrate 10,100 hours of operation at the full 6.9 kW of input power. This is significant in that no other ion propulsion system has demonstrated that kind of duration [10].

Advanced research has been ongoing in the physical design of GITs. Ultimately, conventional GIT performance is limited by the dual grid design. Ion extraction and acceleration occurs simultaneously. The electric potential between the grids is limited to prevent the electric field generated by the grids from permeating the chamber. To prevent this from occurring while still allowing for greater potentials, a dual stage, four grid (DS4G) concept has been investigated. The European Space Agency (ESA) has conducted laboratory tests of a prototypical design and achieved promising results. The DS4G thruster was able to produce typical thrusts of 2.7 mN at an ISP of 14,000 s using

300 W of power. Demonstration of this capability on a small-scale thruster indicates significant potential for high delta-V missions [11].

2.2.3. Magneto-Plasma Dynamic Thrusters

A typical MPDT consists of a central cathode surrounded by an outer anode ring. An arc of current is established between the anode and cathode ionizing a gaseous fuel. The return current in the cathode creates a radial magnetic field which in-turn accelerates the ionized gas axially. Additional electromagnets employed around the anode can be used to stabilize or further accelerate the fuel.

The MPDT design may be well suited to high power, near Earth missions. NASA analysis shows potential for ISPs up to 5000 s using low molecular weight fuels [12]. Additionally, recent studies have shown favorable performance of MPDT for near Earth missions such as geostationary transfer of heavy satellites and round trip travel to the Moon. Those missions would typically draw 100-250 kW of power [13]. However, MPDT thrusters are most efficient at high power input levels. Such demands may require use of fission powered satellites which are technologically immature and politically controversial.

The long term potential for MPDT is promising. However, the technology is currently limited by the severe cathode erosion as a result of the extremely high currents passing through it and the ability to maintain a magnetic field at the high temperatures generated by the thruster [13]. Near term, these thrusters are not good candidates for near Earth satellite maneuver.

2.3 Continuous Thrust Maneuvers

Continuous thrust maneuvers create an additional challenge for modeling. Typical impulsive maneuvers are relatively easy to model. However, the integration of acceleration creates a much more difficult task. Fortunately, using computer simulation, it is still possible to model this type of maneuver. As can be seen in the example documented below, continuous thrust has been explored for its potential as an economic and efficient way to boost satellites into higher orbit with minimal weight and lifetime costs.

Additionally, limited research has been conducted in ascending node alteration. This type of maneuver can alter inclination and accelerate or decelerate regression of the ascending node. If the period or the inclination can be altered in a predictable fashion then a pass over the target can be scheduled.

2.3.1. Eccentricity Manipulation

Traditional orbit raising maneuvers have always been accomplished using manipulation of the satellites eccentricity. Impulsive acceleration at the perigee will result in an increased semi-major axis. The orbit can then be circularized with impulsive apogee acceleration. There has been significant interest in using low-thrust electric propulsion to facilitate transfer of a satellite from its intermediate orbit to full geosynchronous orbit. Traditional chemical propulsion to geosynchronous orbit can be very expensive in terms of fuel and payload size. Use of electric propulsion allows for smaller launch vehicles and larger payloads with a significant penalty in timeliness. Using continuous propulsion at low thrust dramatically increases the time to complete the transfer.

Similarly, the eccentricity can be altered dynamically as part of a mission profile thus slightly altering the period. Alteration of the period in a predictable fashion could result in a responsive capability. Electric propulsion is the likely candidate for such maneuvers. Because electric propulsion methods are significantly more efficient and have substantial lifetimes, they can be used as part of an adaptable mission profile without significant reduction in lifetime.

Research in optimal orbit raising maneuvers abounds for traditional impulsive maneuvers. However, use of continuous electric propulsion for orbit raising has been researched in much less detail. NASA has researched and modeled geosynchronous orbital insertion from a transfer orbit. Using continuous low-thrust from a typical 1.15 N HET operating at an ISP of 2000, the transfer of a 6600 kg satellite was modeled. Starting with an apogee of 35,786 km and a perigee of 185 km, the transfer required approximately 120 days resulting in a circular orbit at 35,786 km. Additionally, the 28.5 starting inclination was reduced to a 0 degree inclination [14].

Dankanich and Byers further explored transfer of communication satellites to geosynchronous orbit using electric propulsion. Modeling was based upon a nominal 4500 kg to 5000 kg communications satellite. Specific impulses of 1000, 1500, and 2100 sec were used. Maneuverability, as indicated by a decreased insertion time, was maximized at a power to mass ratio of approximately 6.2 W/kg for all three ISP values. However, time improvement decayed exponentially indicating little room for improvement beyond that ratio. The models also indicated that insertion times under 100 days for satellites of this size could reasonably be achieved with current electric

propulsion systems but achievement of insertion times less than 30 days are not possible at the power levels currently achieved on operational satellites [15].

While the objective of this research is not to facilitate an orbital transfer, the scope of an orbit raising maneuver is significant and demonstrates the potential for smaller scale manipulation of orbit eccentricity. Research into predictable orbit manipulation for the purpose of achieving a scheduled pass is non-existent. However, the principals of orbital raising maneuvers can be exploited to estimate the abilities of responsive orbital maneuver.

2.3.2. Ascending Node Manipulation

Maneuver outside of the orbital plane can be very expensive. Typically, such maneuvers are avoided. However, there is potential using low thrust electric propulsion to use such a maneuver and alter the plane. Considering the simple polar orbit, such a maneuver could alter the RAAN and thus ground track for a scheduled pass. Research into ascending node alteration is very limited.

C. S. Welch has conducted an in-depth analysis of low-thrust ascending node alteration for minimum fuel usage. A polar orbiting constellation of three satellites orbiting at 824 km was considered. According to his research, a 52.5 degree nodal shift over 160 days would require 10.6 km/s of low thrust acceleration. However, it was also found that altering the semi-major axis and inclination could result in a maneuver costing only 660 m/s to achieve a similar result by using the differential nodal drift rate between the new and original orbit. Once the orbit regressed to the desired location, the orbit semi-major axis and inclination were returned to their original values [16].

Welch found that the more fuel efficient method for altering the RAAN was to alter the satellites inclination and semi-major axis to capitalize on differential nodal drift caused by the asphericity of the Earth. Eastward transfers were induced using continuous thrust maneuvers and fixed thrust angles [16].

Col Newberry also discusses the benefits of nodal transfers. However, he discusses the inefficiency of circular orbits for such maneuvers. Because the apogee velocity of highly-elliptical orbits is significantly lower, the thrust requirement to alter the orbital plane is also significantly lower than for circular orbits. Figure 2.1 shows the

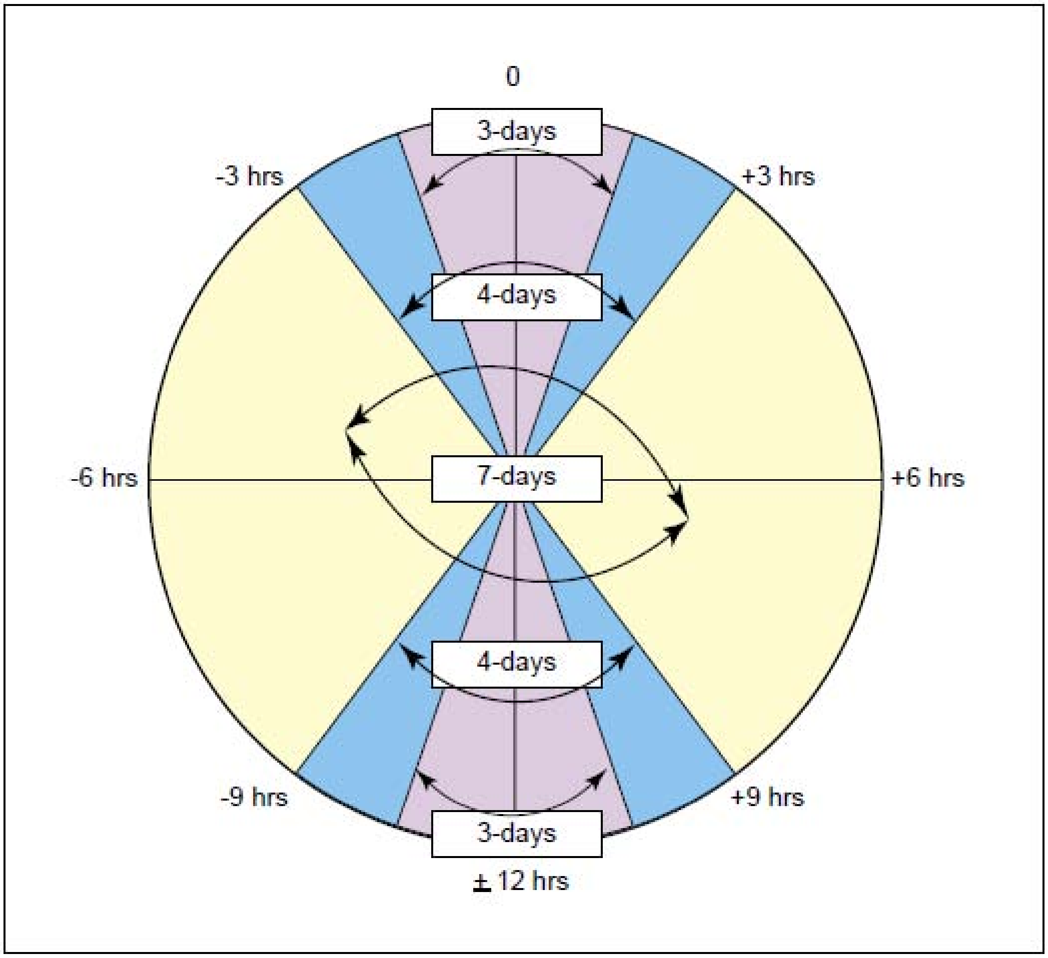

Figure 2.1 Time On Target Performance Based on Lead Time [1]

potential for manipulation of time on target (TOT) for a typical highly-elliptical polar orbit using a nominal low thrust plane change maneuver [1].

2.3.3. Highly-elliptical Low Perigee Orbits

Very little documented research exists on highly-elliptical low perigee orbits. Existing research has been spearheaded by NASA to support the Geospace Electrodynamics Connections (GEC) Mission. The GEC mission was designed to maneuver a constellation of probes to a 130 km perigee altitude over the course of 2 years. The mission profile allowed for the satellite to "dip" into the lower ionosphere for sampling at various times over the short life cycle [17].

This mission was modeled around the periodic usage of traditional impulsive thrusters and propellants. Using a 222 km nominal perigee and 1525 km nominal apogee, 10, 1-week low perigee campaigns were possible. Mission data was modeled on a nearly 1000 kg (total weight) satellite and using a base ISP of 285 s. The study evaluated trading different potential drag coefficients and thruster ISPs to maximize the dry spacecraft weight. Lower drag resulted in greater potential weight and various ISPs affected both the dry mass and propellant mass. Trading between longevity and continuous operation at low perigee was not evaluated [17].

Using the above discussion of thruster technology, nominal thruster performance figures can be derived to model current as well as future capabilities. The discussion of relative orbital research will lend to the selection of certain orbital parameters in the next chapter. Chapter 3 will discuss the selected variables and the methodology used to evaluate the individual orbit scenarios.

3. Methodology

3.1 Design Constants and Variables

In order to accurately assess the performance capabilities of electric propulsion several constant conditions must be assumed. For the purposes of this analysis a single, nominal satellite design was considered. While the satellite attributes are not varied, various generic propulsion schemes were considered. Additionally, certain aspects of the orbital maneuver are kept constant while others are varied. Space is infinite as are the possible orbits that a satellite can be placed in. Only a constrained set of relatively common orbits are considered. Finally, the analysis was conducted around an arbitrarily chosen, yet commercially, scientifically, and politically interesting location.

3.1.1. Satellite Design

The nominal satellite used for this analysis is a design typical of low Earth scientific satellites. Table 3.1 outlines the assumed attributes of the satellite. The selected attributes are commonly achievable design parameters based upon existing satellite designs.

The purpose of this research was not necessarily to select an appropriate thruster design for responsive maneuver. For that reason, performance was evaluated over a range of thruster values as shown in Table 3.2. Based upon the previous discussion of thruster technology, it is assumed that current technology is capable of providing 60 mN of thrust at an ISP of 1750 s when power of 1000 W is available.

Table 3.1 Nominal Satellite Design Attributes

Wet Mass	400 kg
Shape	Hexagonal
Dimensions	2 m hexagonal x 2 m deep
Solar Array	Planar-oriented array
Attitude Control	3 axis control using reaction wheels
Effective Surface Area	4 m^2
Drag Coefficient	3
Power	1200 W

Table 3.2 Nominal Thruster Specifications

	Thruster 1	Thruster 2	Thruster 3	Thruster 4	Thruster 5
Thrust (mN)	1750	2562.5	3375	4187.5	5000
Isp (s)	60	82.5	105	127.5	150

Based upon the literature, further developments are likely to yield thrusters capable of producing 150 mN of thrust at an ISP of 5000 s. Iteratively, the thrusters listed in Table 3.2 were evaluated representing the range of technology readiness. While not considered here, future improvements in satellite power generation will correspond with greater thruster capabilities.

3.1.2. Orbit Selection

Two orbital schemes were evaluated for their potential. Each scheme may be more or less suited to different missions. Highly-elliptical orbits may offer potential for extended dwell time over a certain target. Conversely, the same orbit, rotated 180 degrees could be used for a recurring low perigee track for near Earth sampling. Additionally, highly-elliptical orbits offer better efficiency for alteration of the ascending node. Circular orbits provide consistent coverage over the entire path. Sensors or missions that are highly sensitive to altitude are better suited to circular orbits. Figure 3.1 displays the common classical orbital elements used in the orbital schemes.

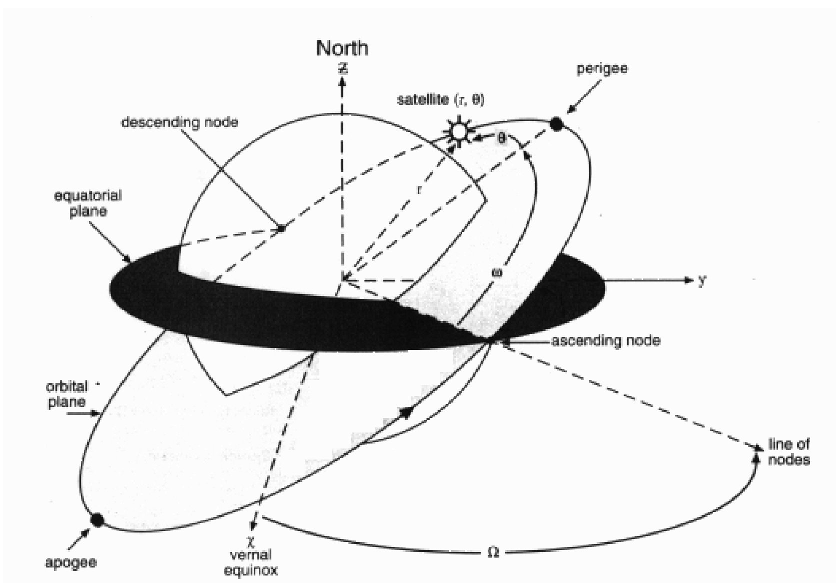

Figure 3.1 Classical Orbital Elements [19]

The elliptical orbit models for low perigee passage used the parameters identified in Table 3.3. The time coverage models used the parameters identified in Table 3.4. For both scenarios, an orbit with the perigee occurring over the northern hemisphere was derived and access rates for a given target where found, if applicable.

Table 3.3 Low Perigee Orbit Parameters

	Min Value	Max Value
Apogee altitude	622 km	18,622 km
Perigee altitude	100 km	100 km
Inclination	40 deg	40 deg
Argument of Perigee	90 deg	90 deg
RAAN	0 deg	0 deg
True Anomaly	0 deg	0 deg

Table 3.4 Highly-elliptical Orbit Parameters

	Min Value	Max Value
Apogee altitude	18,622 km	18,622 km
Perigee altitude	622 km	622 km
Inclination	40 deg	90 deg
Argument of Perigee	90 deg	90 deg
RAAN	0 deg	0 deg
True Anomaly	0 deg	0 deg

With a highly-elliptical orbit, many of the orbital schemes forced the satellite to pass through the Van Allen Radiation Belts. Significant radiation effects are encountered from the inner band which is centered approximately 1200 km above the Earth's surface. Additionally, radiation from the outer band, which is centered approximately 25,500 km above the Earth's surface, can affect spacecraft [2]. In order for a satellite to repeatedly travel through these regions, special design considerations must be incorporated.

The minimum inclination of 40 degrees was selected as it is appropriate for the nominal target location used in the analysis. Furthermore, initial values for the argument of perigee, RAAN, and true anomaly will remain consistent throughout analysis.

Nearly circular orbits were also evaluated for their potential in scheduled access with a ground target. The initial orbit was established with a typical circular low Earth orbiting scheme. This circular orbit was then analyzed using continuous thrust maneuvers to vary the eccentricity.

Table 3.5 Circular Orbit Parameters

	Initial Value
Apogee altitude	623 km
Perigee altitude	622 km
Inclination	40 deg
Argument of Perigee	90 deg
RAAN	0 deg
True Anomaly	0 deg

3.1.3. Target Selection

Recognizing that the majority of domestic interest lies in a region relatively close to 40 degrees N latitude, a representative target would remain close to this latitude. For the purpose of this analysis Dayton, Ohio was selected as a nominal target. Specifically, Dayton's latitude is 39.7589 degrees N.

3.1.4. Evaluation Period

Each simulation was conducted over the same period. The analysis period was arbitrarily chosen to begin with the previously discussed orbital parameters at 1 Aug 2007 12:00 UTC. The period concluded on 1 Sep 2007 12:00 UTC.

3.1.5. Thrust Profiles

To simplify the analysis, the thrust profile for each scenario is greatly simplified. In most cases, thrust is directed along the velocity vector from perigee to apogee, constituting one thrust cycle. Optimally, the thrust angles would change continuously so as to maintain the perigee of the orbit while simultaneously raising the apogee, thus performing similar to an impulsive thrusting maneuver at perigee. However, to facilitate analysis, the profile is simplified greatly.

For the low perigee analysis, a total of 100 thrust cycles was accomplished and then the satellite was allowed to continue, un-thrusted, for the remainder of the evaluation period. At the completion of the evaluation period, the final apogee and perigee altitudes was recorded.

The thrust cycles used to manipulate the eccentricity of the circular and elliptical orbits to so analyze potential pass opportunities were based upon an incremented sequence of cycles. For example, a scenario without any thrust was evaluated for the

entire period. Subsequently, the scenario was reinitiated with one thrust cycle and coverage for the entire period was recorded. The scenario was repeated with the number of thrust cycles increasing each time until 50 thrust cycles were accomplished.

While using a similar scheme to measure the coverage for each successive thrust cycle, the RAAN change was modeled with the thrust directed normal to the orbital plane. Specifically, the normal direction would be the vector generated by the crossing the velocity vector into the vector pointing at nadir. The anti-normal direction would correspond to a vector pointing in the direction opposite of that just defined. Thrust was alternately directed in the normal direction during the ascent from perigee to apogee and then directed in the anti-normal direction during the descent to apogee. Conversely, the opposite was also modeled with thrust occurring first in the anti-normal direction then in the normal direction. These thrust methods are in no way considered optimum. However, they do offer a simple profile for analysis.

Additionally, the number of thrust cycles chosen for each scenario was arbitrarily chosen. The use of 100 thrust cycles to maintain low perigee orbit has no significance other than providing a common basis for comparison. Similarly, the 50 thrust cycles used for the elliptical and circular orbit coverage analysis merely provides a standard baseline for comparing the maneuvers. Figure 3.2 depicts the vectors previously referenced.

3.2 Evaluation Methods

Using STK, the various orbital schemes were analyzed for the coverage and gaps in coverage for each orbital scheme. For low perigee orbits, an access was only counted if the target was within the line-of-sight of the satellite for 30 seconds or greater. This, in theory, allows for a sensor to collect the mission specific data.

Each of the incrementally-improved thruster configurations was independently evaluated for all orbital schemes. Each orbital scheme was then iteratively evaluated for each variable combination.

The High Precision Orbit Propagator (HPOP) was chosen to model the motion of the satellite. Per the software description for HPOP found in STK, equations of motion are integrated using the Runge-Kutta-Fehlberg method of 7th order with 8th order error control. Drag is incorporated into the simulations and is based upon the Jacchia-Roberts Atmospheric Density Model. Solar radiation pressure and gravitational effects caused by

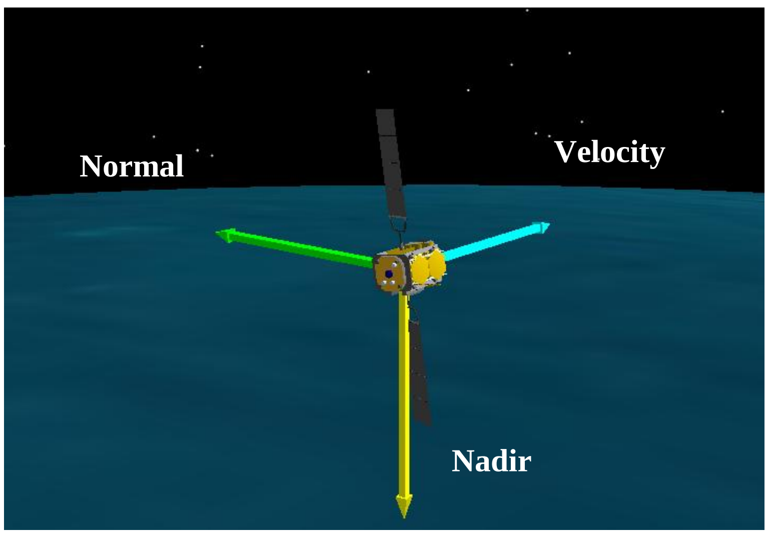

Figure 3.2 Satellite Vectors

lunar and solar bodies are also incorporated into HPOP. Finally, STK states that the gravitational variation of the Earth is modeled using WGS84/EGM96 data incorporated into the propagator.

Atmospheric density can significantly affect the orbit of a satellite. Because this scenario evaluated very low perigee orbits, the effect was even more pronounced and will

dramatically affect the longevity of the satellite. Figure 3.3 and Figure 3.4 show the nominal atmospheric density over Dayton, OH at the start time for the scenario.

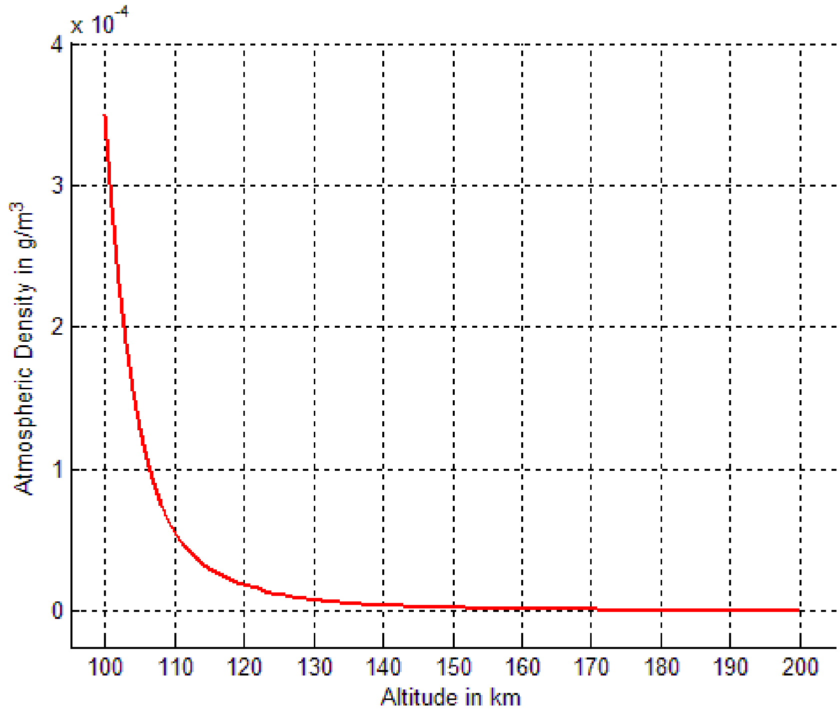

Figure 3.3 Low Altitude Atmospheric Density Over Dayton, OH on 1 Aug 2007

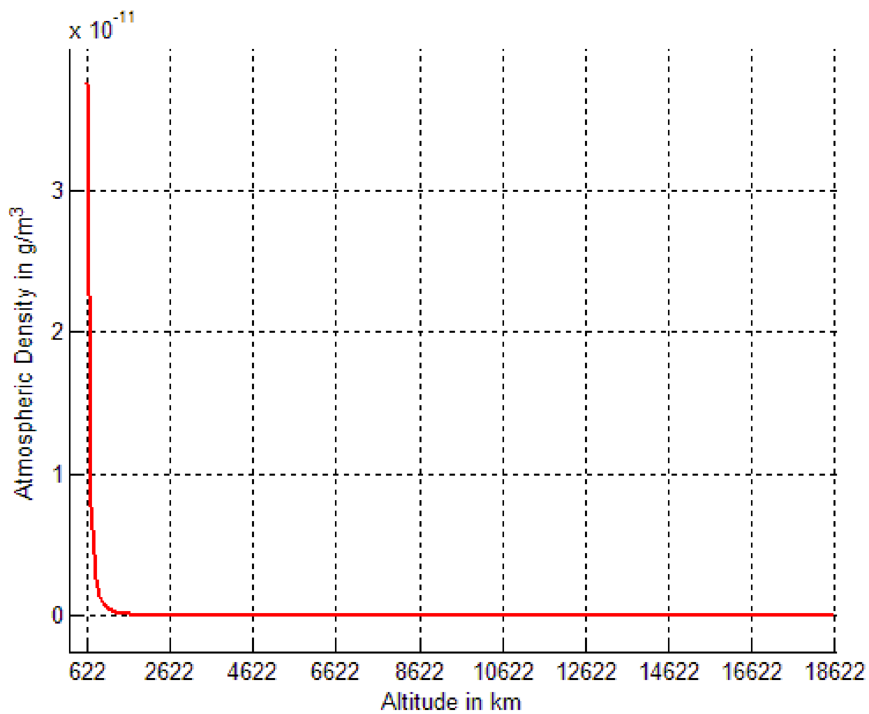

Figure 3.4 High Altitude Atmospheric Density Over Dayton, OH on 1 Aug 2007

The process used to collect data for each scenario is outlined below in Figure 3.5 through Figure 3.7. These flow charts demonstrate the steps taken and the associated software used to model and collect the data. Additionally, Figure 3.8 outlines the algorithm used to process the access times collected from each report.

Several different figures are used to represent the findings. To demonstrate target access, the in-view time of the target for the entire analysis period is plotted as a coverage band for each successive thrust cycle sequence. For example, the access periods for a single thrust maneuver are plotted for the entire period. Then, the scenario is reset and two thrust maneuvers are plotted. The scenario is repeated until the desired number of thrust cycles is accomplished. At the top of these figures, the total accessibility of the target is plotted with the bands representing times where the target could be accessed using one of the successive thrust cycles.

To display the availability of the target for access, each thruster cycle is once again considered. However, the percentage at any given number of thrust cycles is the coverage provided by that thrust cycle and all previous. For example, if the percentage available for access was 10% at five thrust cycles, that would mean that only 10% of the 31 day period was within a window where a scheduled access could occur using zero to five thrust cycles.

Next, in Chapter 4, the results and analysis from each of the scenarios is discussed in detail. For the low perigee orbit analysis, the final orbital parameters for each orbital scheme are identified. Additionally, for the coverage analysis, the percentage of potential coverage is discussed.

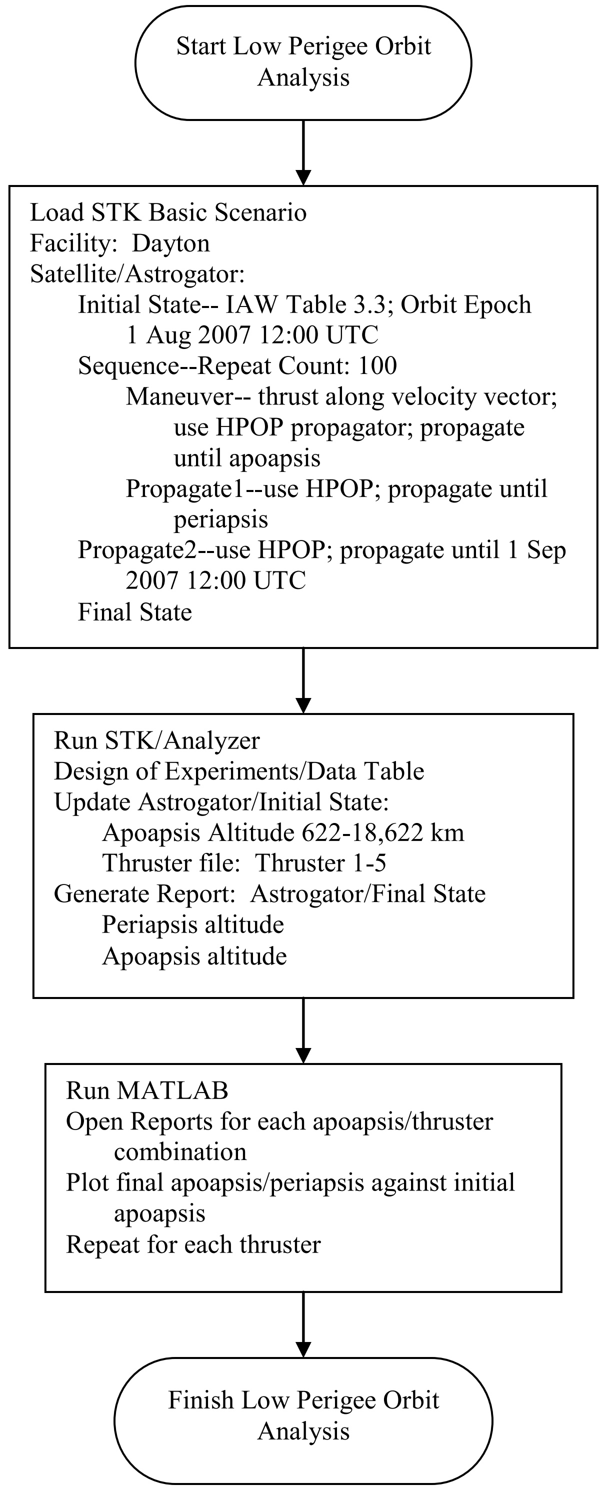

Figure 3.5 Low Perigee Orbit Analysis

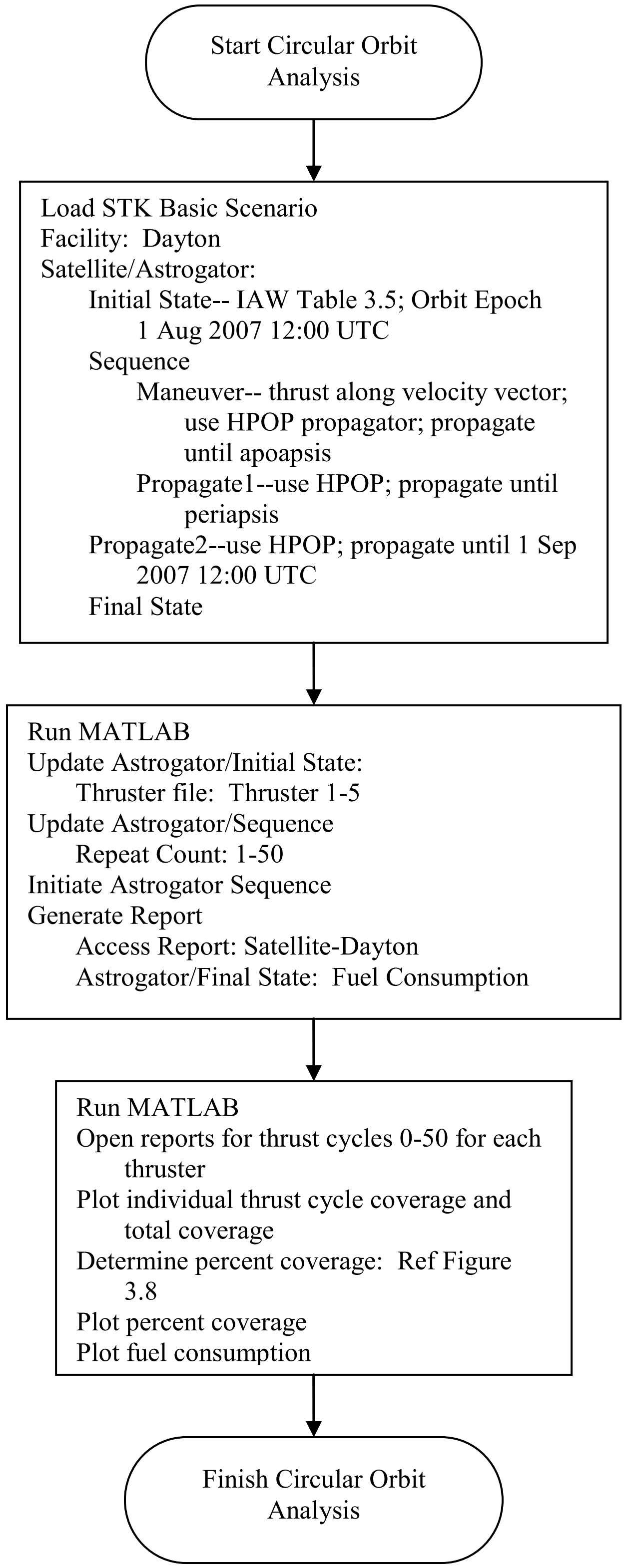

Figure 3.6 Circular Orbit Analysis

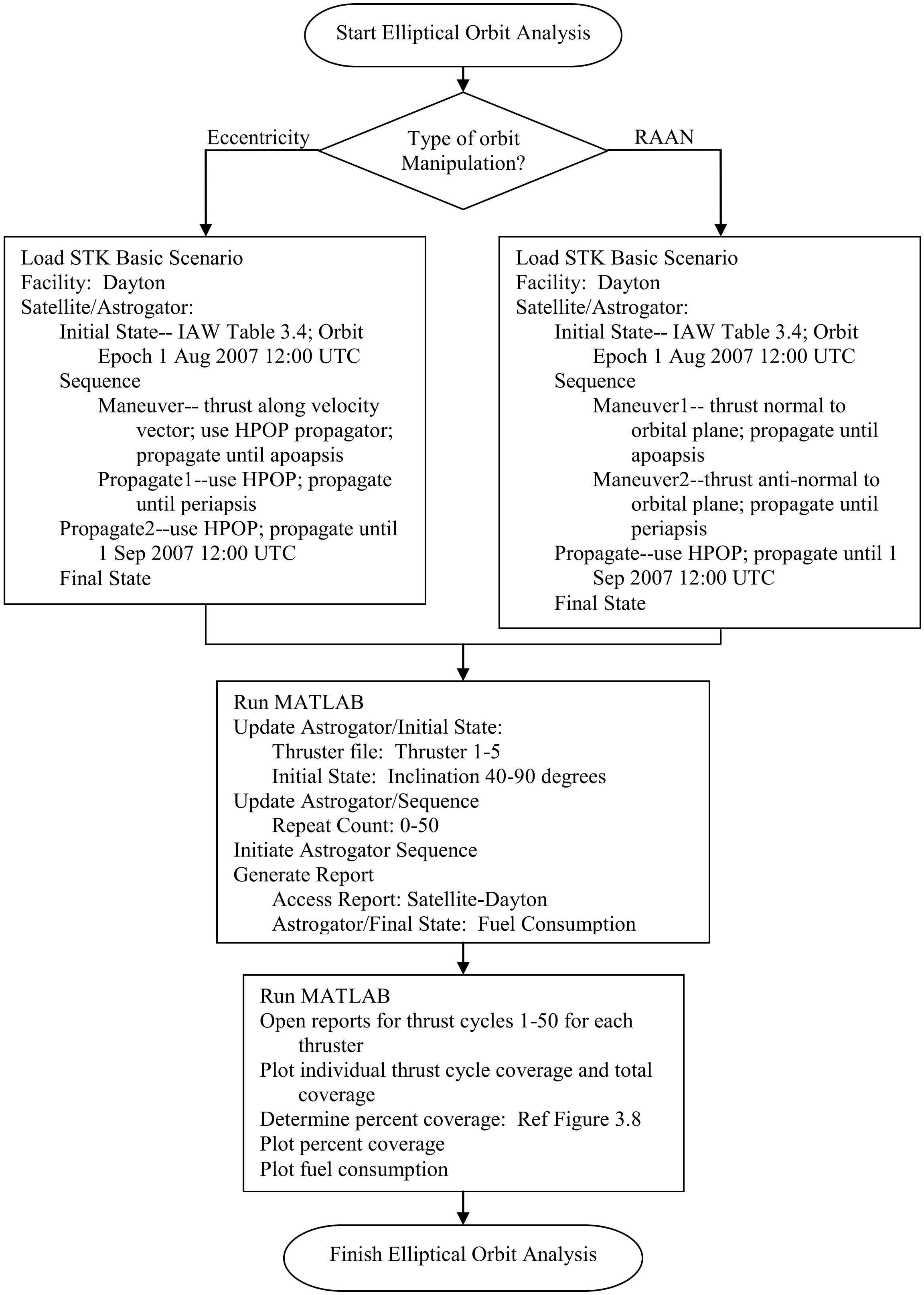

Figure 3.7 Elliptical Orbit Analysis

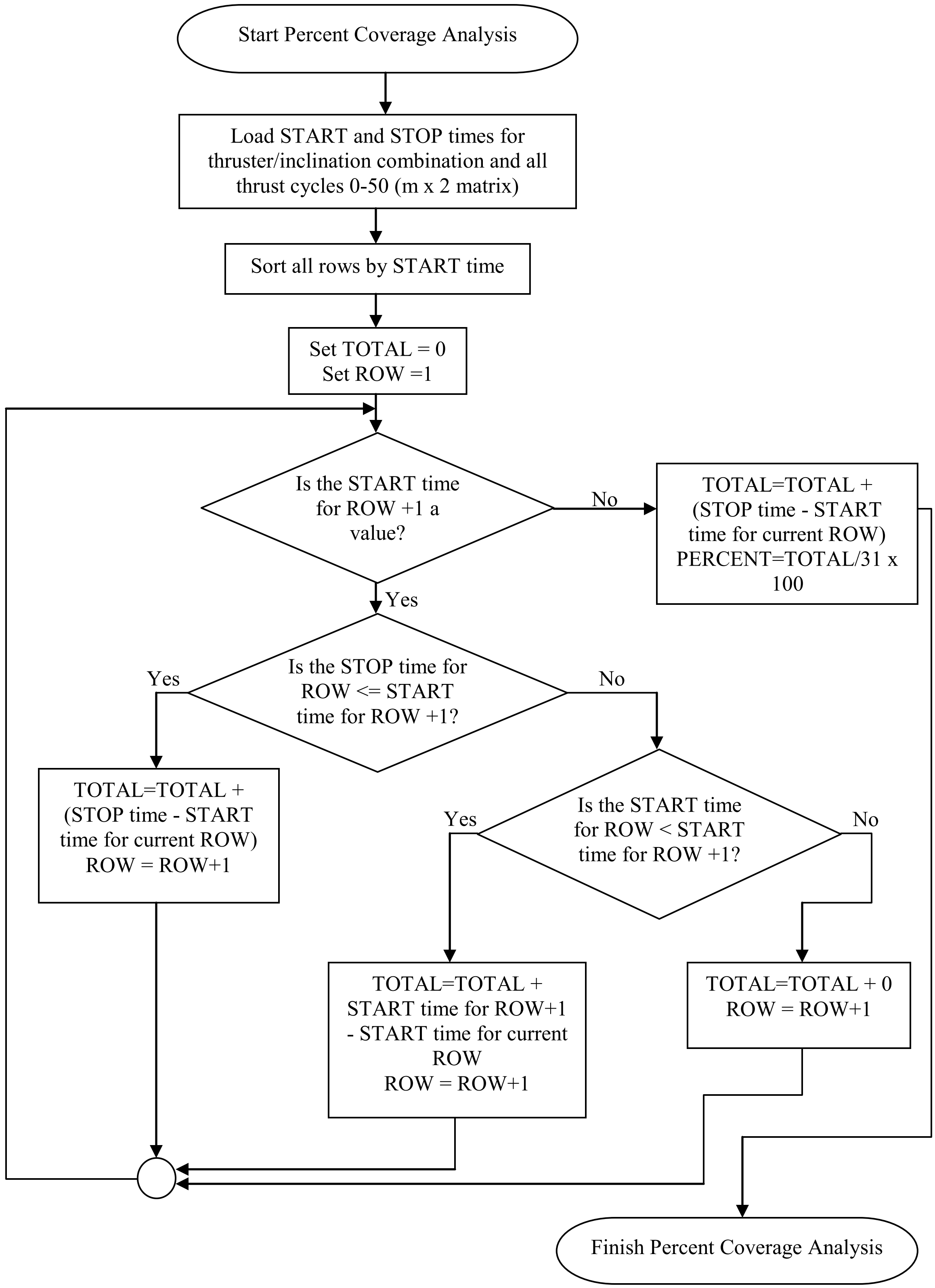

Figure 3.8 Percent Coverage Analysis

4. Results and Analysis

4.1 Low Perigee Orbits

Analysis of extremely low perigee orbits was conducted to determine feasibility. Figure 4.1 through Figure 4.10 demonstrate the success of each orbit based upon the final apogee and perigee of the orbit. The initial perigee altitude for each case was 100 km. The initial apogee ranged from 622 km to 18,622 km.

Thrusters were fired at perigee along the velocity vector. Thrust was terminated at apogee. The thrust-coast cycle was repeated 100 times. Following the maneuver cycle, the satellite was allowed to coast for the remainder of the evaluation period. The apogee and perigee altitudes reflected in the figures are the quantities modeled at the termination of the evaluation period.

Additionally, because the atmospheric effects are most pronounced at low altitude, the initial apogee range between 622 km and 2622 km is critical to orbit sustainment over the period. To model this critical portion of the orbit, the altitudes between were iteratively modeled.

Each of the five thrusters is identified numerically, referring to the thruster designations found in Table 3.2. For example, Thruster 1 corresponds to the thruster producing 60 mN of thrust and with an ISP of 1750 s and represents current thruster capabilities. Thruster 5 corresponds to the thruster producing 150 mN of thrust and with an ISP of 5000 s representing advanced thruster technologies available in the relatively near term.

To provide reference, each orbit schemes was analyzed without thrust to determine the feasibility of that orbit. At all of the considered starting apogee altitudes, the satellite reentered the atmosphere in a relatively short time, failing to maintain orbit for the duration of the analysis period.

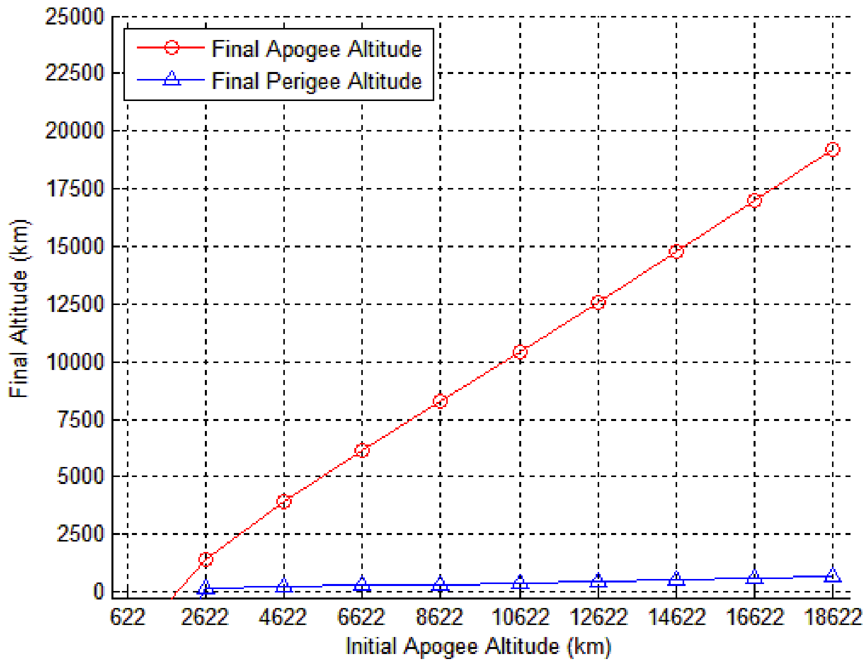

Figure 4.1 Low Perigee Altitudes for Thruster 1 (622-18,622 km Initial Apogee)

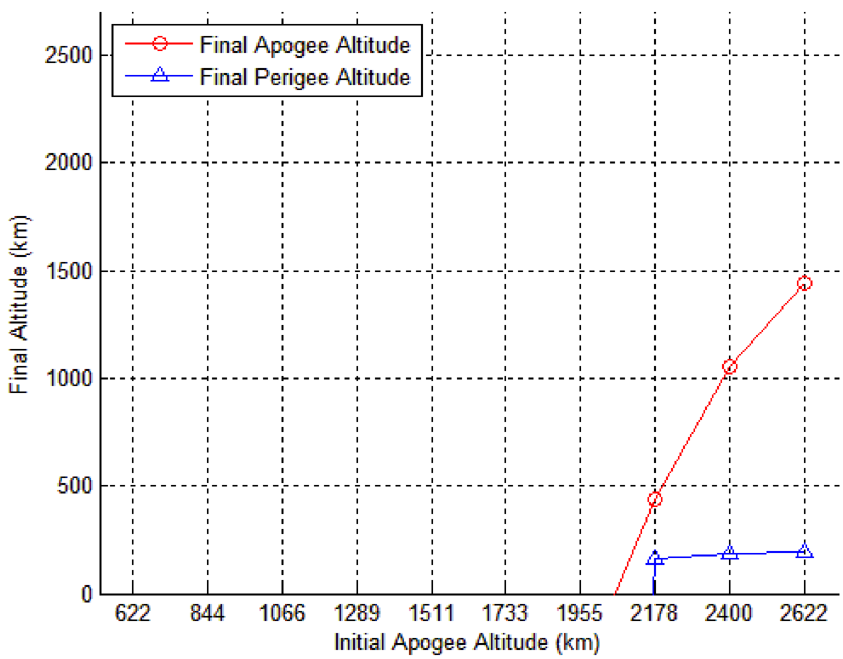

Figure 4.2 Low Perigee Altitudes for Thruster 1 (622-2,622 km Initial Apogee)

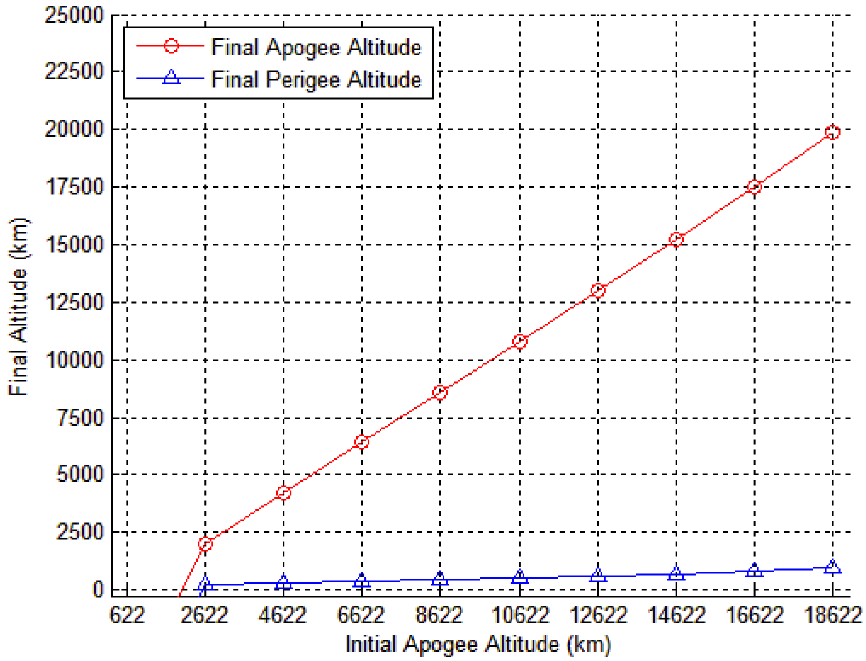

Figure 4.3 Low Perigee Altitudes for Thruster 2 (622-18,622 km Initial Apogee)

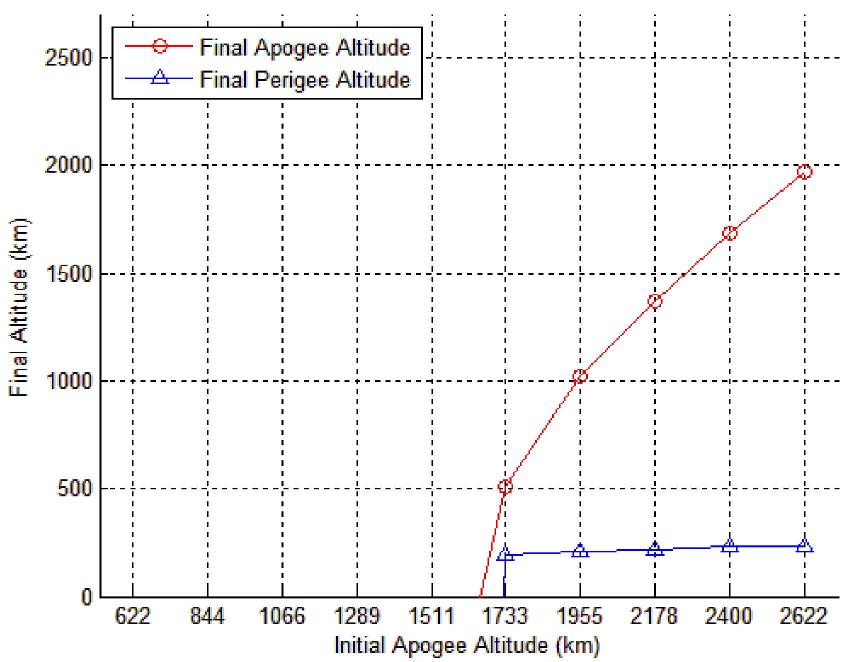

Figure 4.4 Low Perigee Altitudes for Thruster 2 (622-2,622 km Initial Apogee)

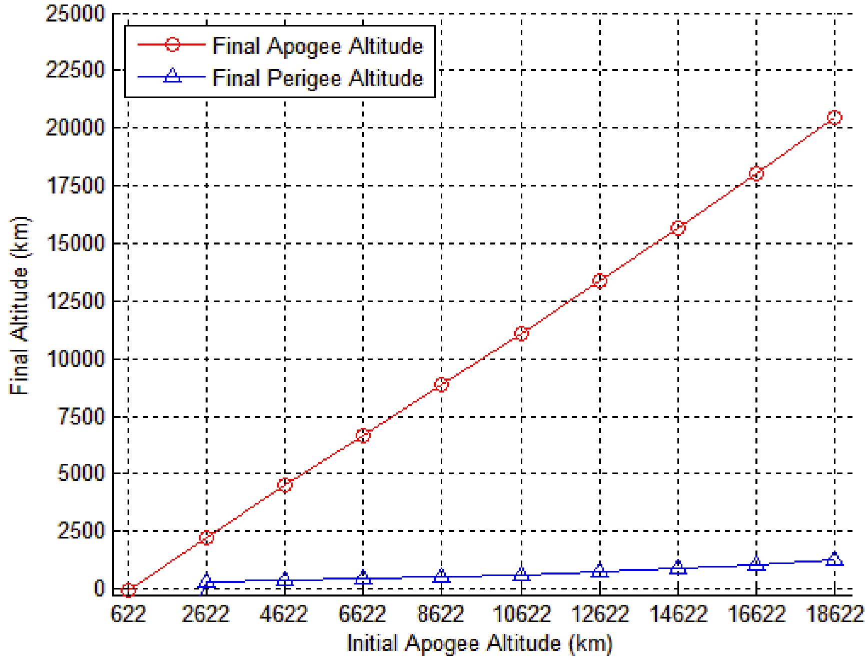

Figure 4.5 Low Perigee Altitudes for Thruster 3 (622-18,622 km Initial Apogee)

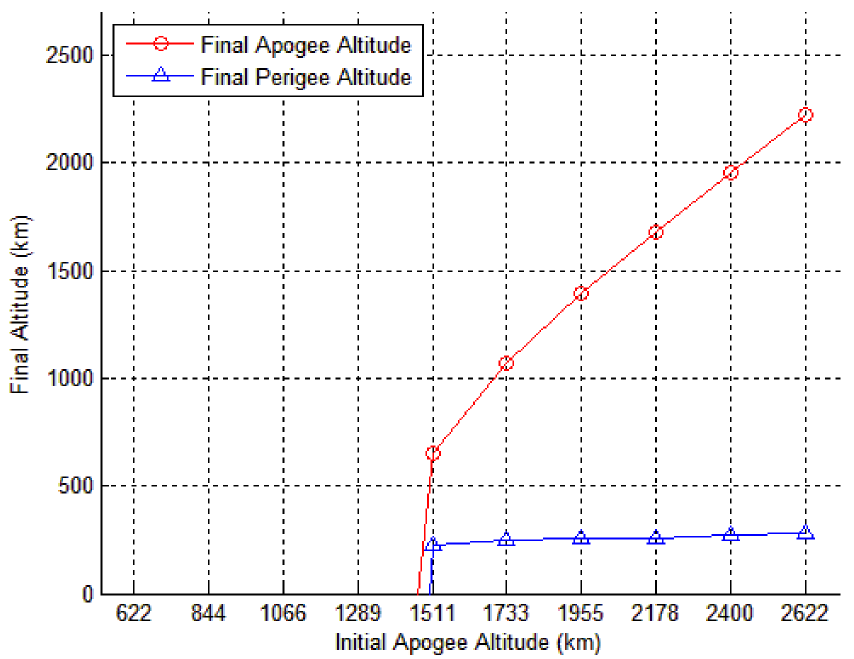

Figure 4.6 Low Perigee Altitudes for Thruster 3 (622-2,622 km Initial Apogee)

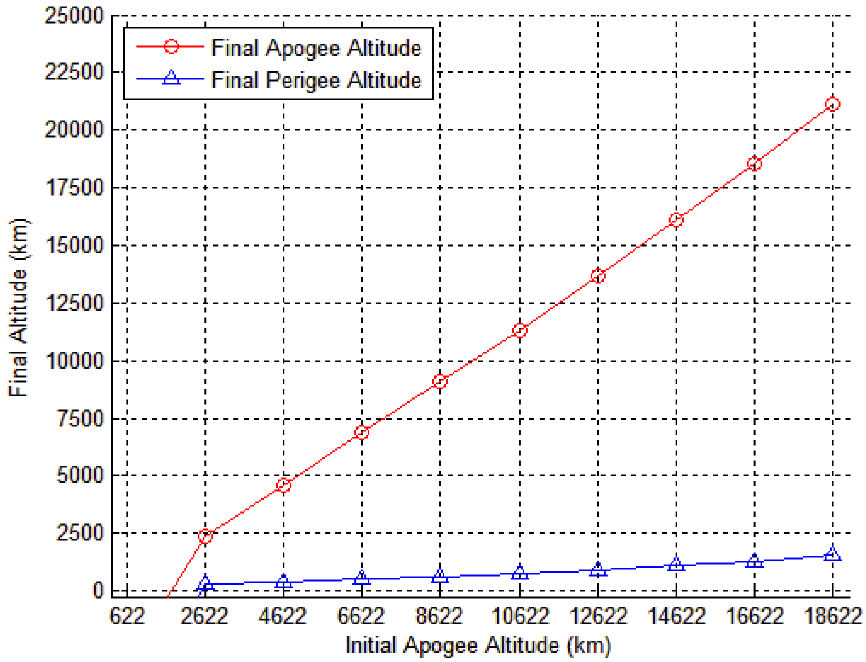

Figure 4.7 Low Perigee Altitudes for Thruster 4 (622-18,622 km Initial Apogee)

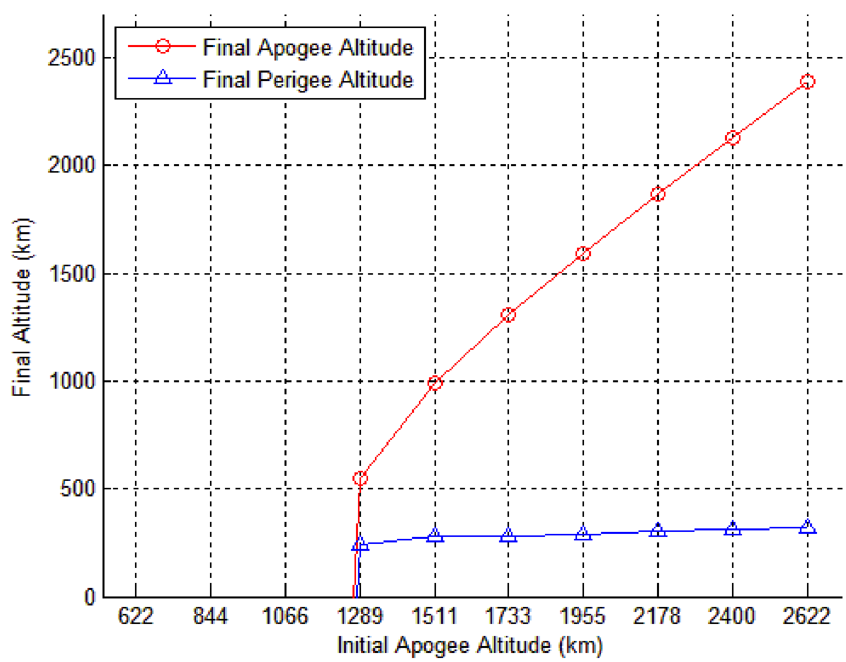

Figure 4.8 Low Perigee Altitudes for Thruster 4 (622-2,622 km Initial Apogee)

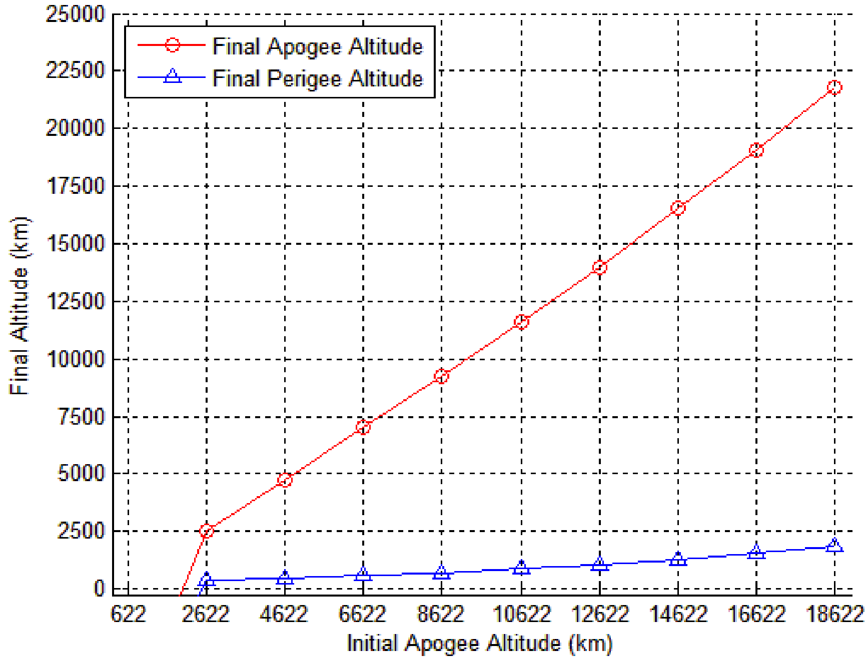

Figure 4.9 Low Perigee Altitudes for Thruster 5 (622-18,622 km Initial Apogee)

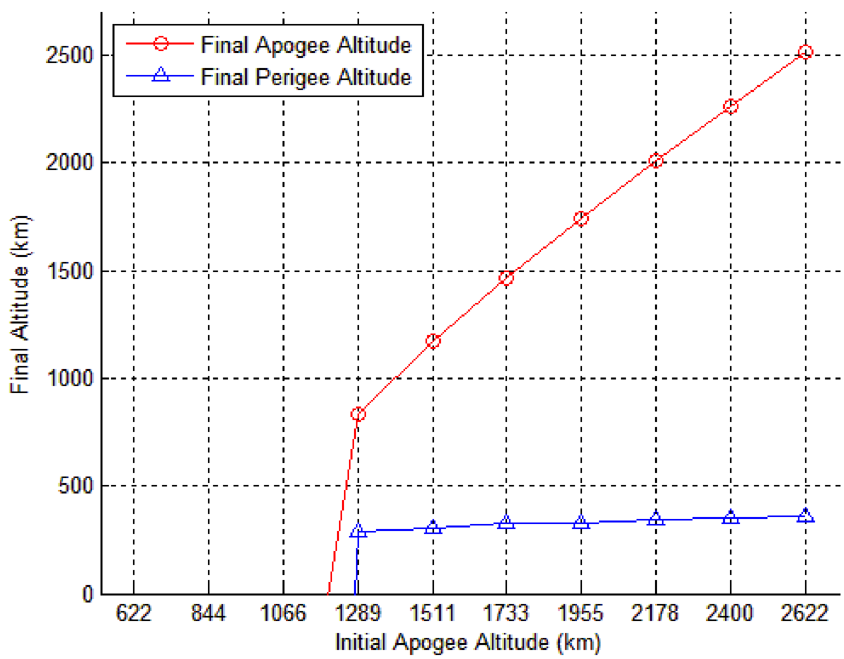

Figure 4.10 Low Perigee Altitudes for Thruster 5 (622-2,622 km Initial Apogee)

The very low perigee orbit analysis yielded significant feasibility data. None of the thruster combinations could maintain an orbit with a 622 km initial apogee altitude and resulted in negative apogee and perigee altitudes at the end of the 31 day period. The lack of apogee height does not allow for a long enough period of continuous thrust to overcome the significant drag encountered at 100 km perigee.

With a 2622 km starting apogee, the satellite was able to remain aloft for the duration of the analysis period using each of the thrusters. However, none of the thrusters were able to maintain the initial apogee of 2622 km over the analysis period and apogee altitude was lost. Thruster 5 finished the period with an apogee height of nearly 2500 km and Thruster 1 finished the analysis period with an apogee altitude of just under 1500 km. This low overall energy of this orbit is attractive because it allows for lower launch costs. However, the mission life at current technology levels would be severely limited.

The 60 mN of thrust provided by Thruster 1 does not support continuous orbit until the initial apogee is raised above 14,622 km. Once above that apogee height, enough duration in the period at the low thrust level available will maintain the orbit until fuel is exhausted. Thruster 2 can maintain the orbit when the initial perigee is above 12,622 km. Thruster 3 can maintain the orbit when the initial apogee is established above 8,622 km. Thruster 4 can maintain the orbit when the initial apogee is above 6,622 km. Finally, Thruster 5 was capable of maintaining the orbit when the initial apogee was in excess of 4,622 km

While not part of this study, thrusters above 105 mN are capable of actually increasing the apogee when started from 18,622 km apogee. The ability to maintain a low perigee orbit appears to depend on at least two critical factors. The altitude of apogee determines the amount of time available for each thrust maneuver. Because the thrust period is equal to half of the

period for each orbit, a longer period will inevitably improve longevity. The low force exerted by electric propulsion thrusters appears to be at a threshold of capability for providing true orbit maneuverability. While 60 mN of thrust will slow the degradation of all orbits considered, it will not prevent decay indefinitely.

Additionally, fuel consumption can eventually limit the mission life. Table 4.1 shows the fuel consumption for each thruster and initial apogee. Based upon a starting fuel mass of 100 kg, the 60 mN thruster consumed as much as 3.5% of its fuel in 31 days. For short duration missions, this may be acceptable but for extended operations, the fuel cost may be prohibitive.

Table 4.1 Fuel Consumption (kg) for Continuous Thrust During Very Low Perigee

Initial Apogee Altitude (km)	Thruster Type				
	1750 Isp 60 mN	256.2 Isp 82.5 mN	3375 Isp 105 mN	4187.5 Isp 127.5 mN	5000 Isp 150 mN
622	N/A	N/A	N/A	N/A	N/A
2622	1.090	1.055	1.039	1.030	1.026
4622	1.350	1.296	1.271	1.259	1.252
6622	1.611	1.544	1.514	1.499	1.492
8622	1.885	1.806	1.771	1.755	1.749
10,622	2.174	2.082	2.044	2.028	2.023
12,622	2.478	2.375	2.333	2.318	2.316
14,622	2.796	2.682	2.639	2.625	2.629
16,622	3.130	3.006	2.962	2.952	2.962
18,622	3.479	3.345	3.302	3.299	3.318

The optimal solution to maintain an orbit will exist where the efficiency of the thruster is highest and the initial apogee of the orbit allows for an adequate thrust period. The 127.5 mN thruster used on an orbit starting at apogee heights above 14,622 km decrease the fuel consumption to 2.5% for the 31 day period. Not considering fuel used for typical orbit maintenance or the decreased fuel costs as the mass of the vehicle decreases over time, a 40 month life expectancy may be possible.

4.2 Circular Orbit

The circular orbit was established, initially, with a 622 km perigee altitude and a 623 km apogee altitude to establish a common argument of perigee. This ensures that all scenarios are initiated from a common point. Continuous thrust was applied along the velocity vector from perigee to apogee. The satellite was then allowed to coast back to perigee un-thrusted. This cycle was repeated iteratively from 1 to 50 times. Each progressively larger cycle of thrust maneuvers and the resulting coverages for the month were recorded. Additionally, an un-thrusted orbit initiated with the same parameters as the thrusted orbit was recorded for each scenario. Below, in the total coverage charts, each line represents the period of time that the satellite had line of site access to Dayton, OH for each thrust scenario. At the top of each figure, the total coverage provided by all thrust sequences over the entire period is shown. While it is not apparent when viewing the total coverage chart, the access periods are actually much smaller. For this reason, access charts for the two days at the end of the evaluation period are included showing the actual time coverages. For the remaining scenarios, the end of period figures will not be included.

Additionally, a figure showing the percentage of the total period available for coverage and the fuel usage for the maneuver sequence is included. This percentage represents the

percentage of the total period that an access can be achieved using from 1 to 50 thrust maneuvers. Fuel usage is a measure, in kg, of the fuel used for each cumulative sequence.

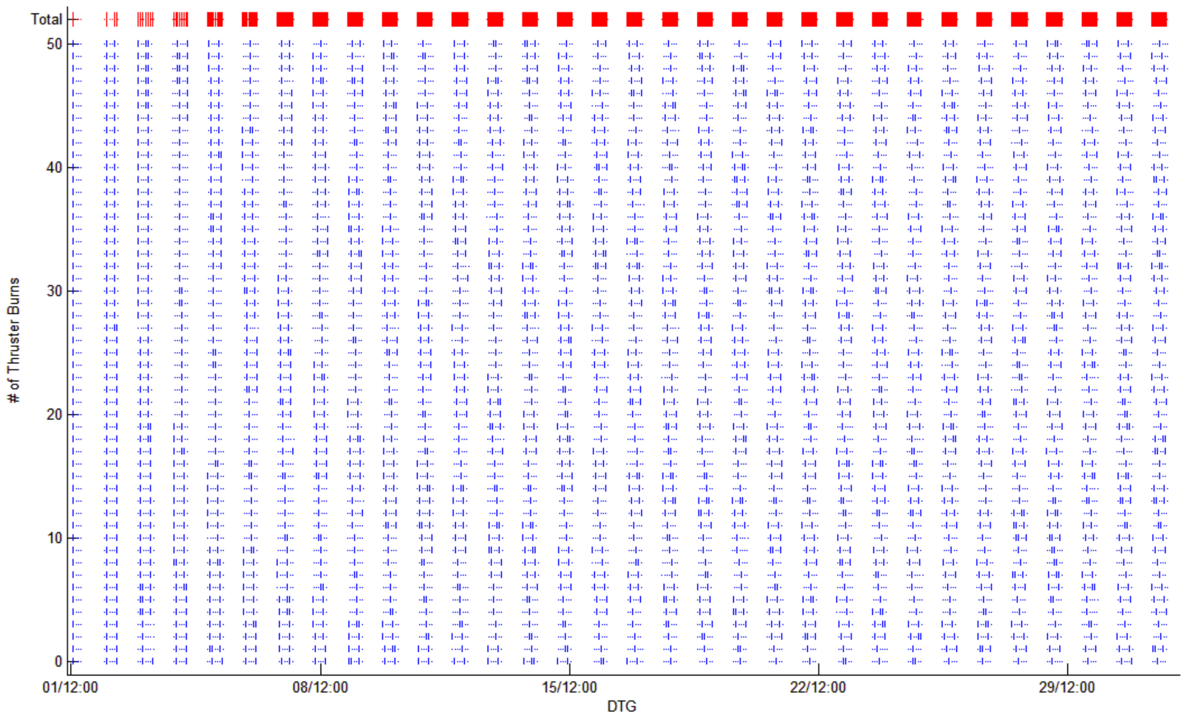

Figure 4.11 Target Access Bands for 30 Day Period Using Thruster 1

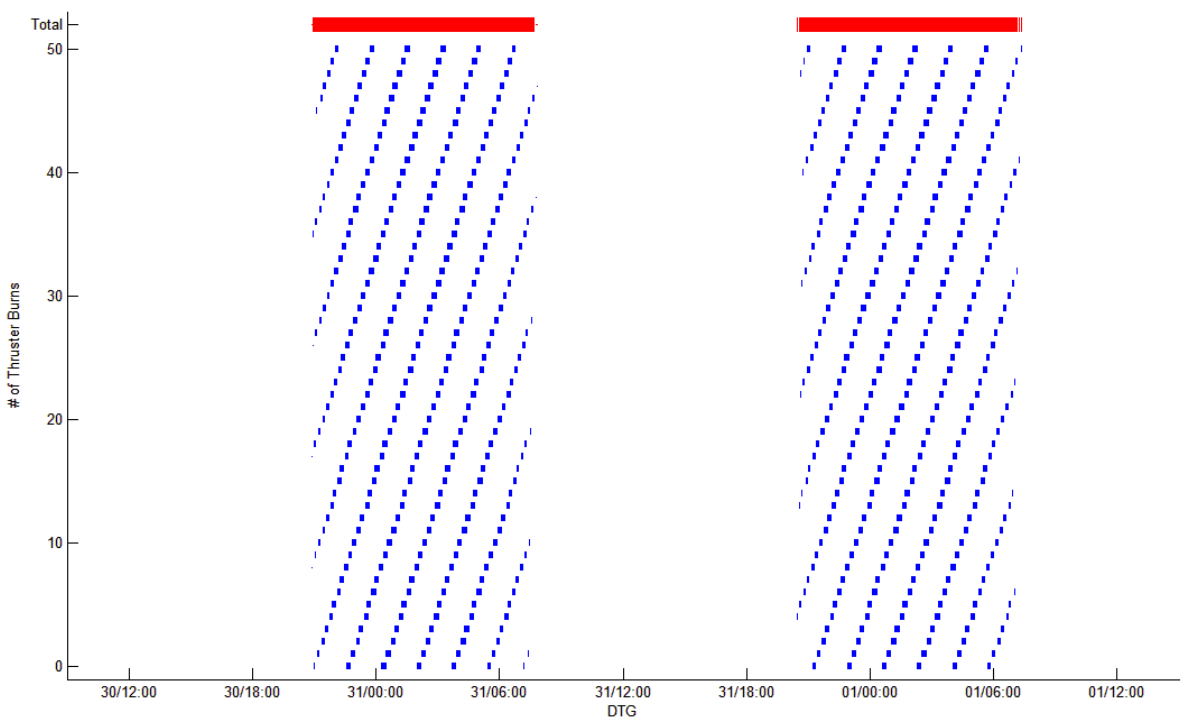

Figure 4.12 Target Access Bands for 2 Day Period Using Thruster 1

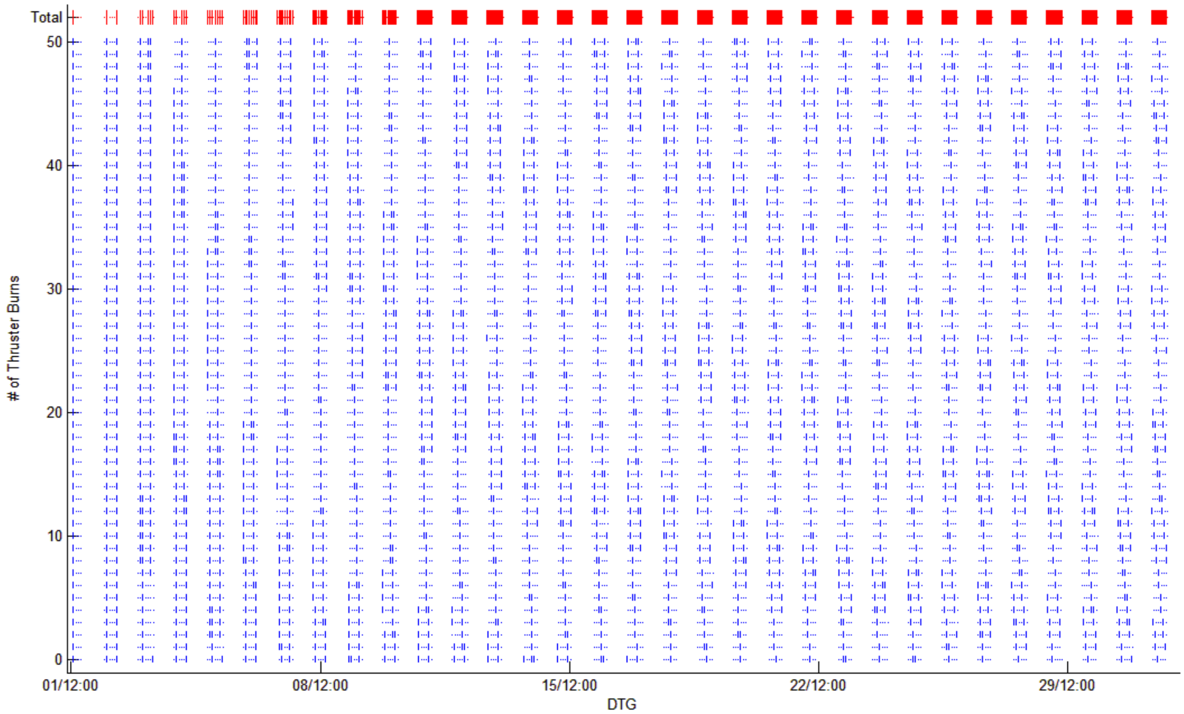

Figure 4.13 Target Access Bands for 30 Day Period Using Thruster 2

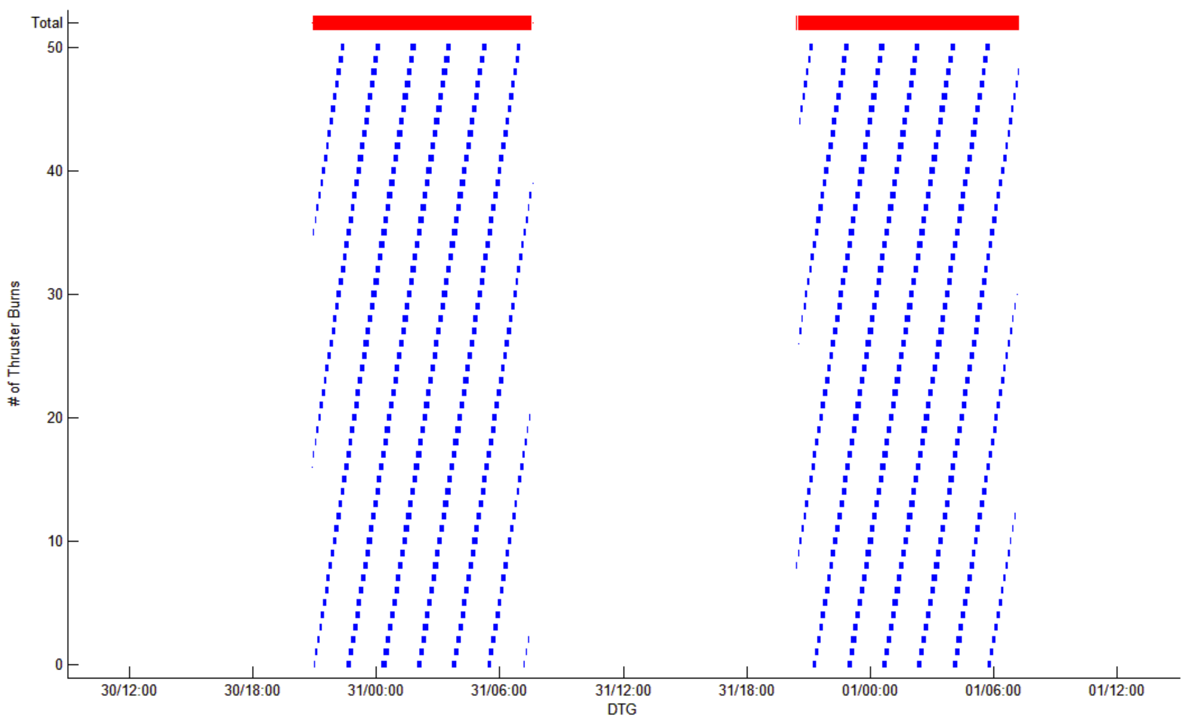

Figure 4.14 End of Period Coverage Using Thruster 2

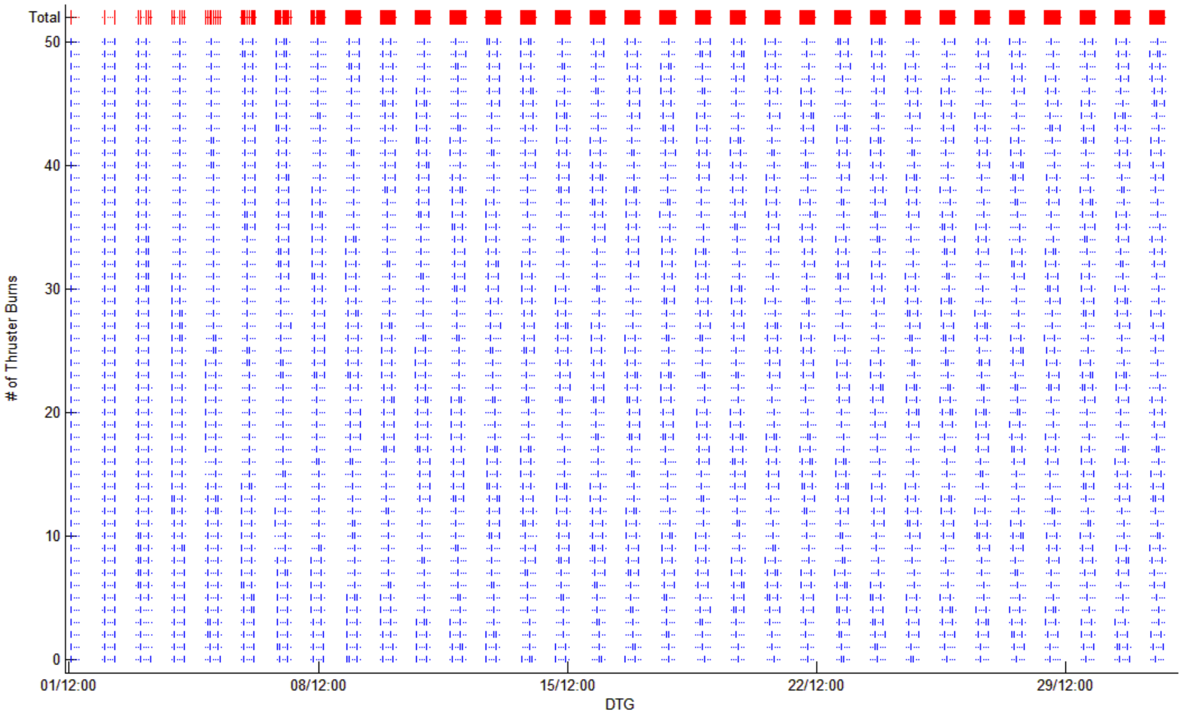

Figure 4.15 Target Access Bands for 30 Day Period Using Thruster 3

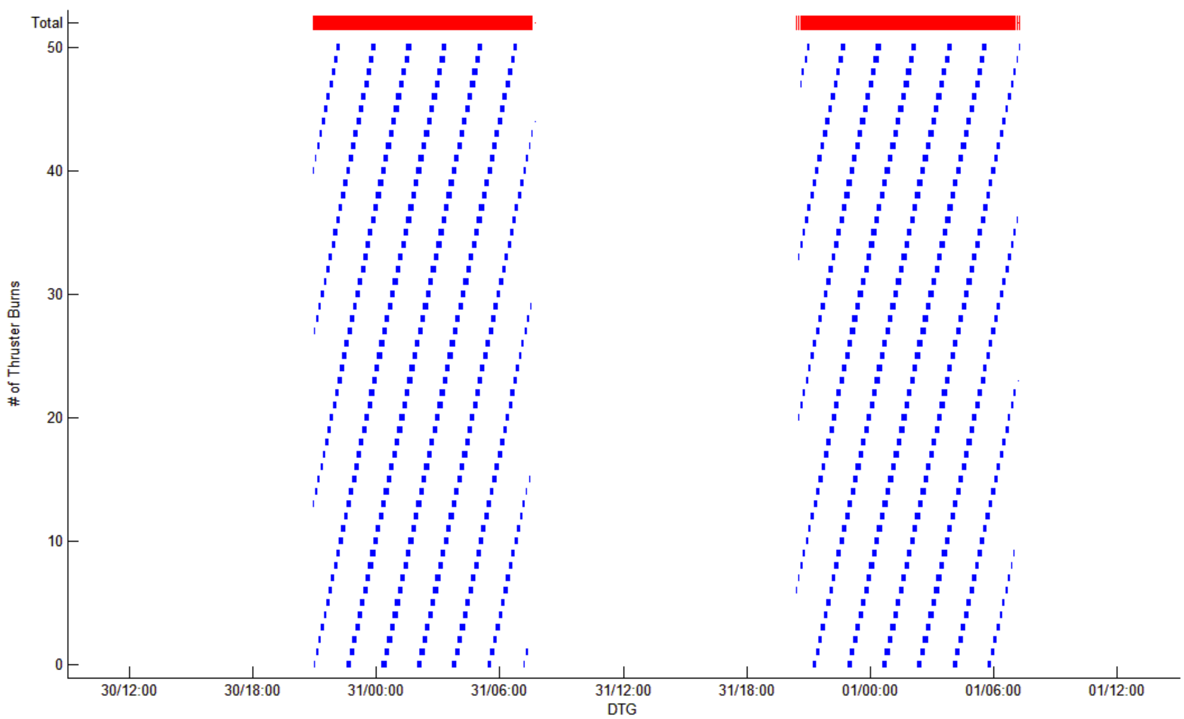

Figure 4.16 End of Period Coverage Using Thruster 3

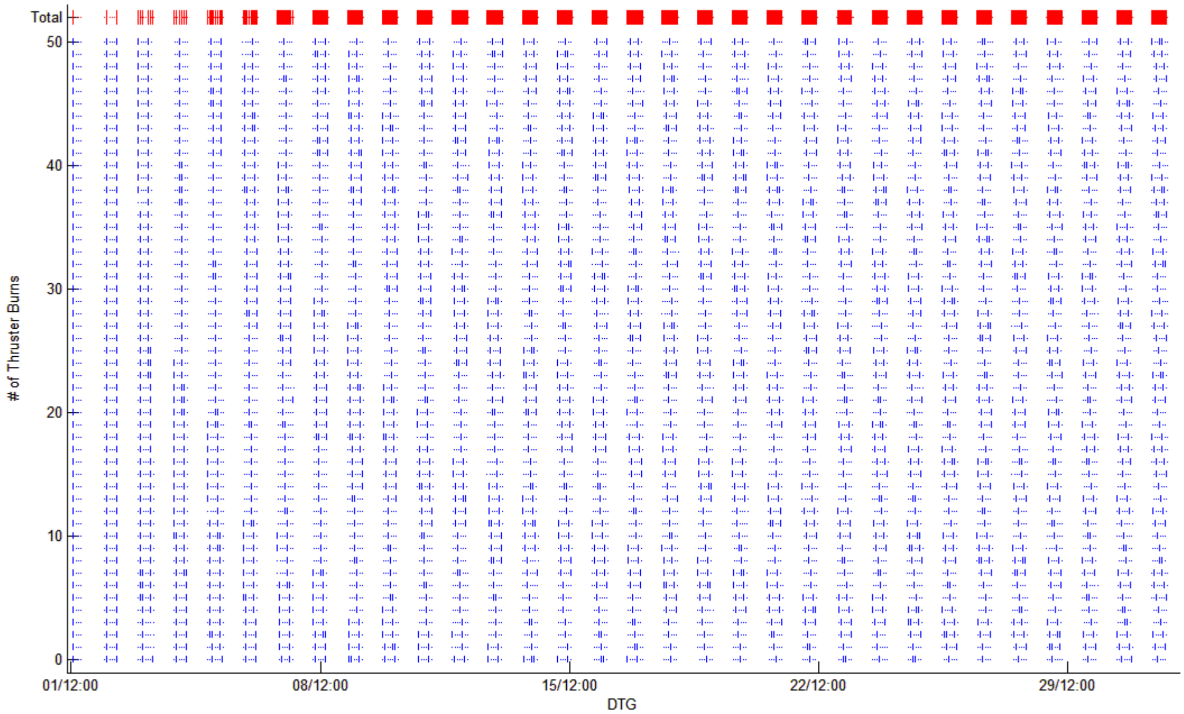

Figure 4.17 Target Access Bands for 30 Day Period Using Thruster 4

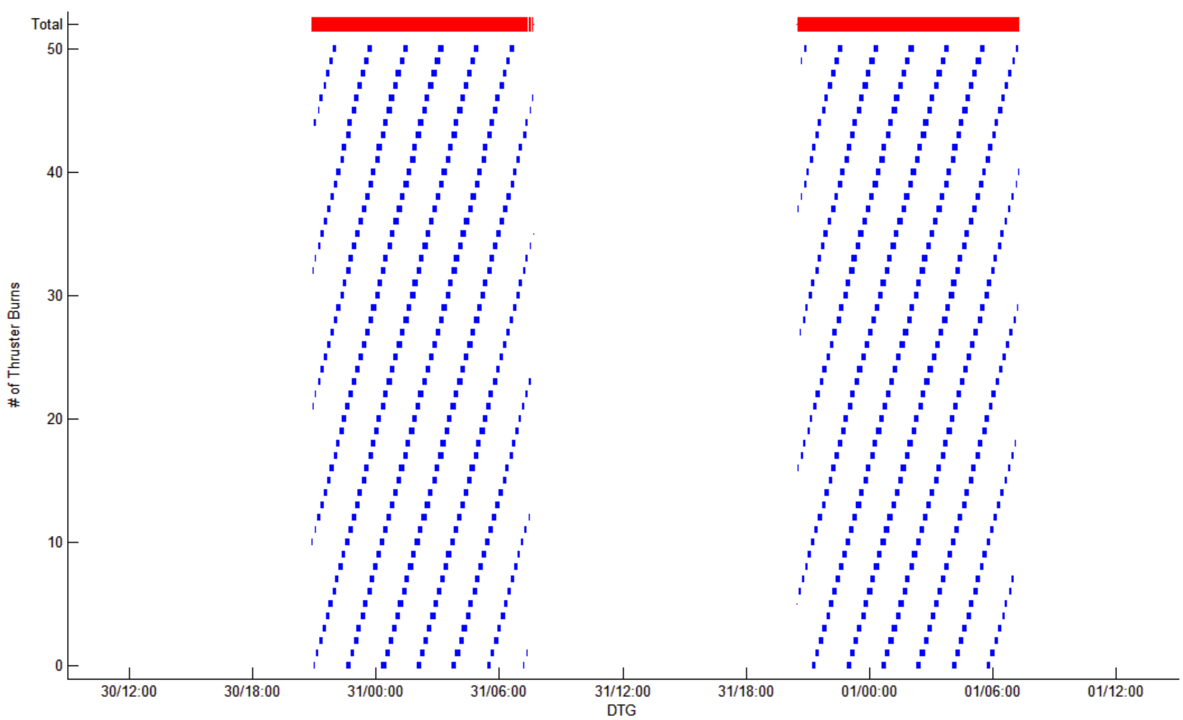

Figure 4.18 End of Period Coverage Using Thruster 4

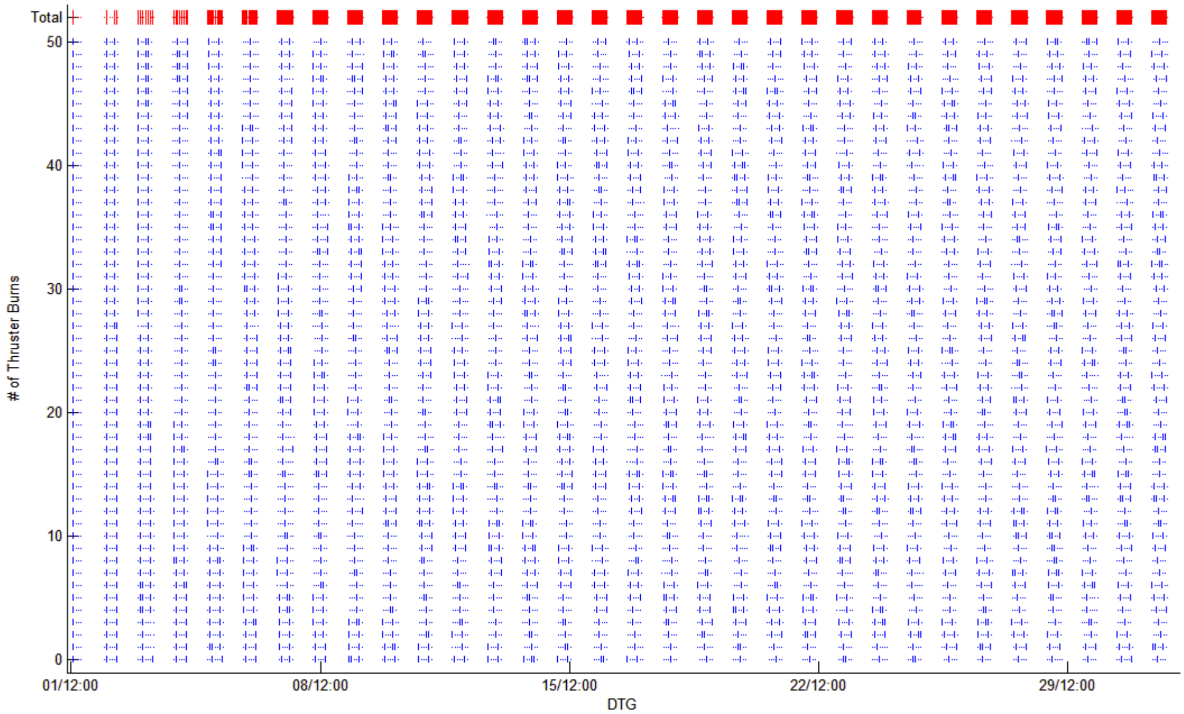

Figure 4.19 Target Access Bands for 30 Day Period Using Thruster 5

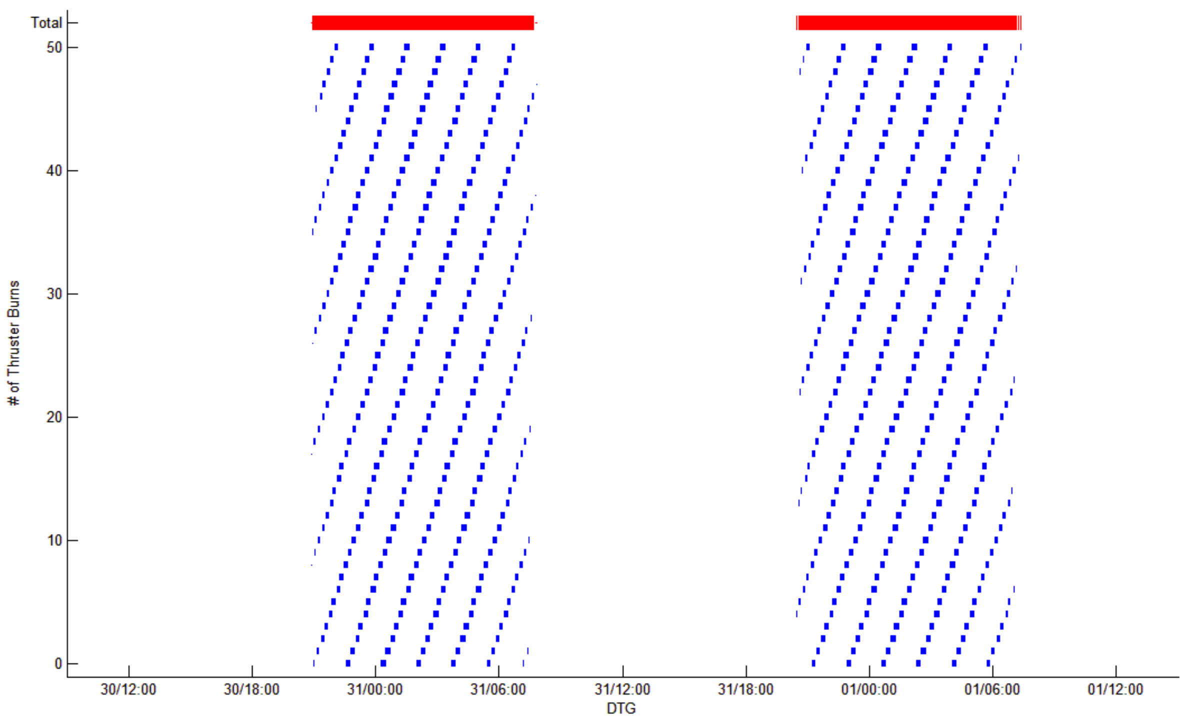

Figure 4.20 End of Period Coverage Using Thruster 5

As can be seen in the above coverage charts, the coverage is not significantly impacted by the thruster used. Any difference in coverage occurs in the first couple of thrust maneuvers. By the 6th day of the period, the coverage for each thruster becomes consistent. Complete coverage is not obtained in any of the circular orbit analysis. However, it can be argued that complete coverage is achieved during the window of opportunity offered by the nodal regression rate. Because the eccentricity and period are relatively constant, the periods of access offered by the nodal regression are unchanged. The gaps in the total coverage reflect periods where the ascending node has regressed to a point where the satellite is unable to have access to the target. Likely, altering the inclination and hence the nodal regression rate, or changing the eccentricity and ultimately the period of the orbit could eliminate these gaps. Within those periods of access, however, coverage is complete. The majority of coverage is obtained within the first 20 maneuvers after which improvement slowly tapers off to a maximum period coverage of approximately 38%.

To further improve the coverage, regression of the ascending node and perigee must be minimized with inclination and altitude. Of course, once the inclination and altitude are altered, the coverage would need to be modeled again.

Below, are the coverage and fuel usage estimates for each thruster. Because the orbit is nearly circular and the thrust period is relatively small, very little difference, if any, is noted in the fuel consumption. Additionally, the coverage is indifferent to the thruster used. For all thrusters, the majority of coverage improvements are made within the first 20 maneuvers after which little is gained. Because the maneuver does not significantly affect the nodal regression or the period, the gaps in total coverage remain largely unavailable for access and therefore improvements fall off to a much lower rate.

The baseline coverage provided by an un-thrusted satellite in the same orbit is only 5%. With 20 maneuvers from the 60 mN thruster, coverage jumps to nearly 30% at a cost of only .1 to .2 kg of fuel. With a 100 kg nominal fuel mass, the maneuver has a great deal of potential for scheduled access. The approximate period for a satellite at that altitude is 90 minutes. Therefore, 30% coverage is possible with as little as 30 hours of maneuver time.

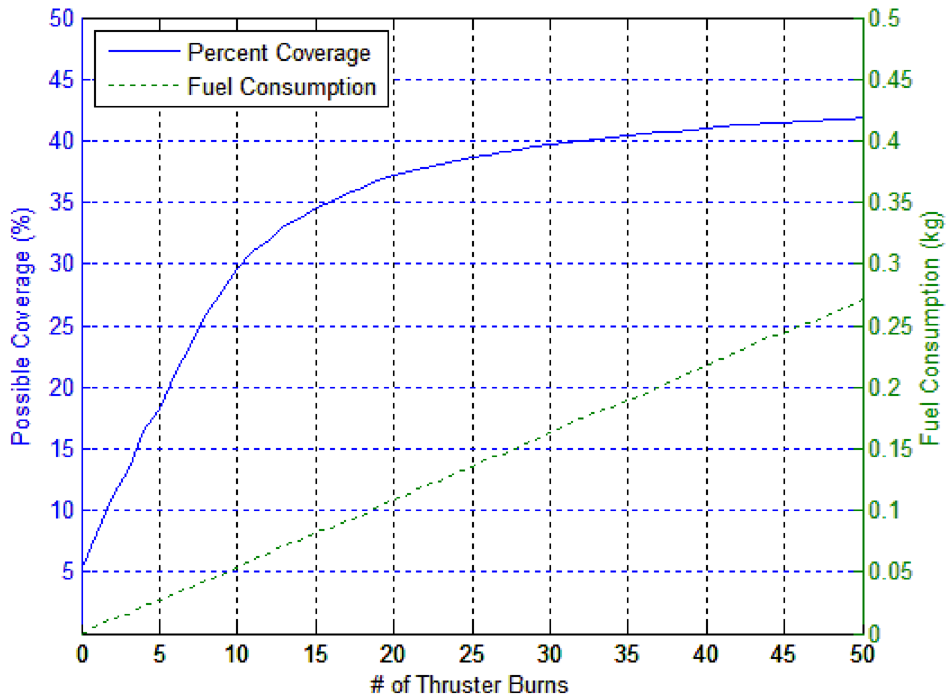

Figure 4.21 Availability of Target for Access and Fuel Consumption Using Thruster 1

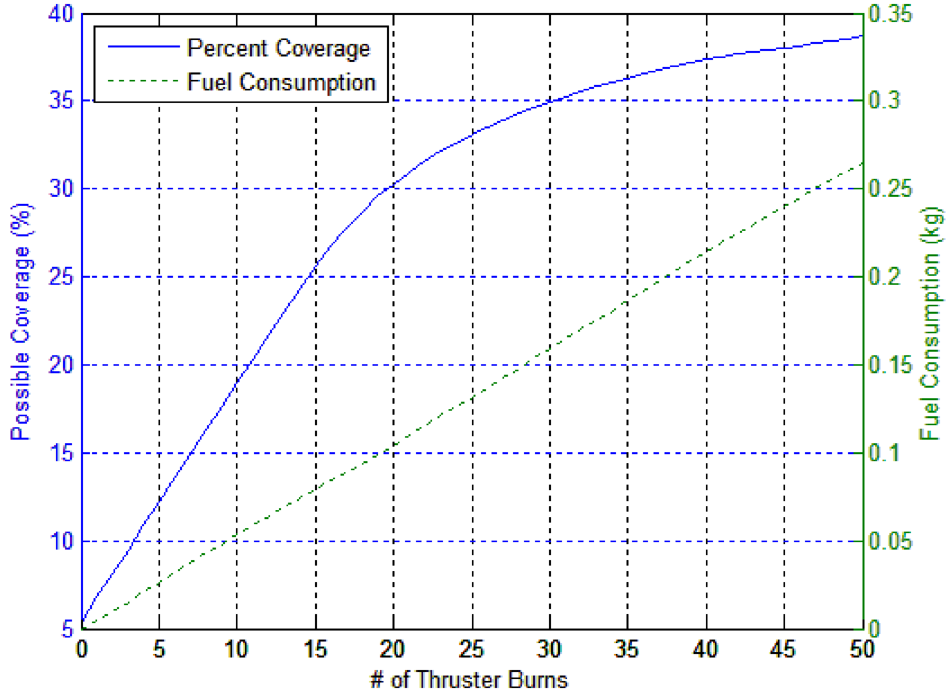

Figure 4.22 Availability of Target for Access and Fuel Consumption Using Thruster 2

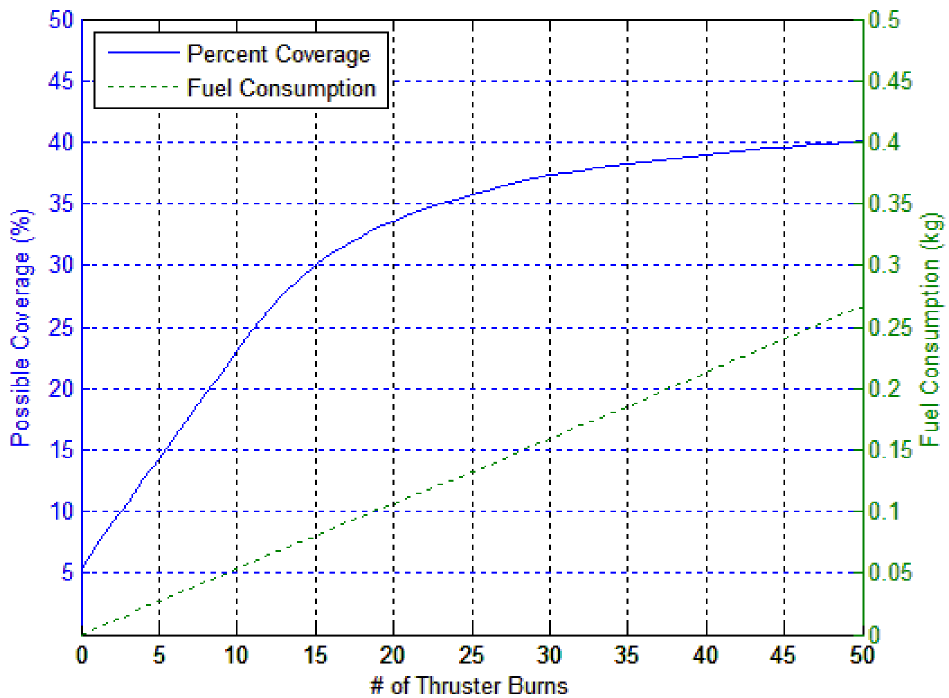

Figure 4.23 Availability of Target for Access and Fuel Consumption Using Thruster 3

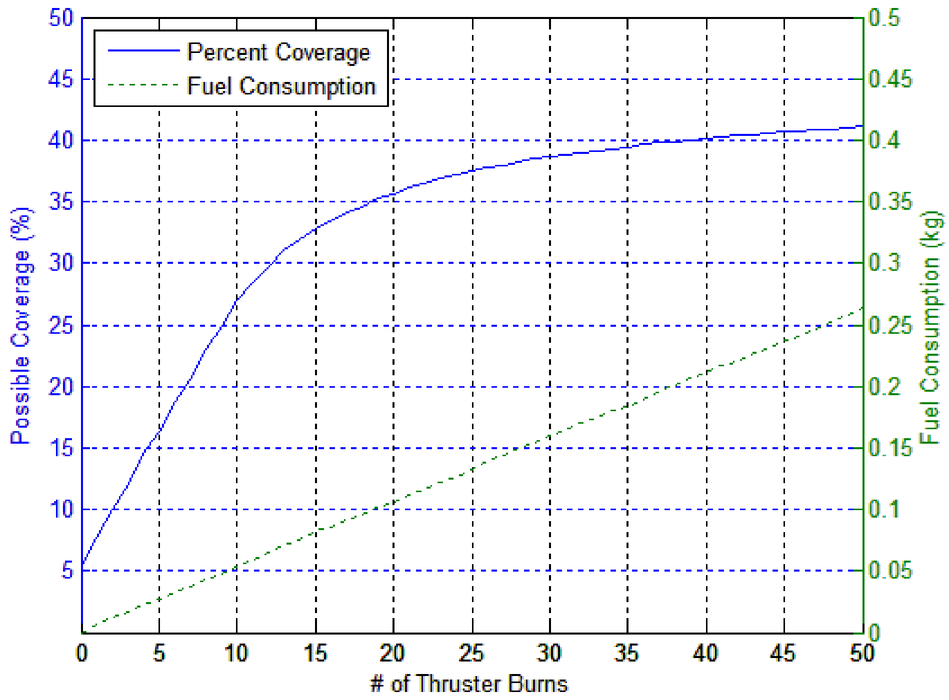

Figure 4.24 Availability of Target for Access and Fuel Consumption Using Thruster 4

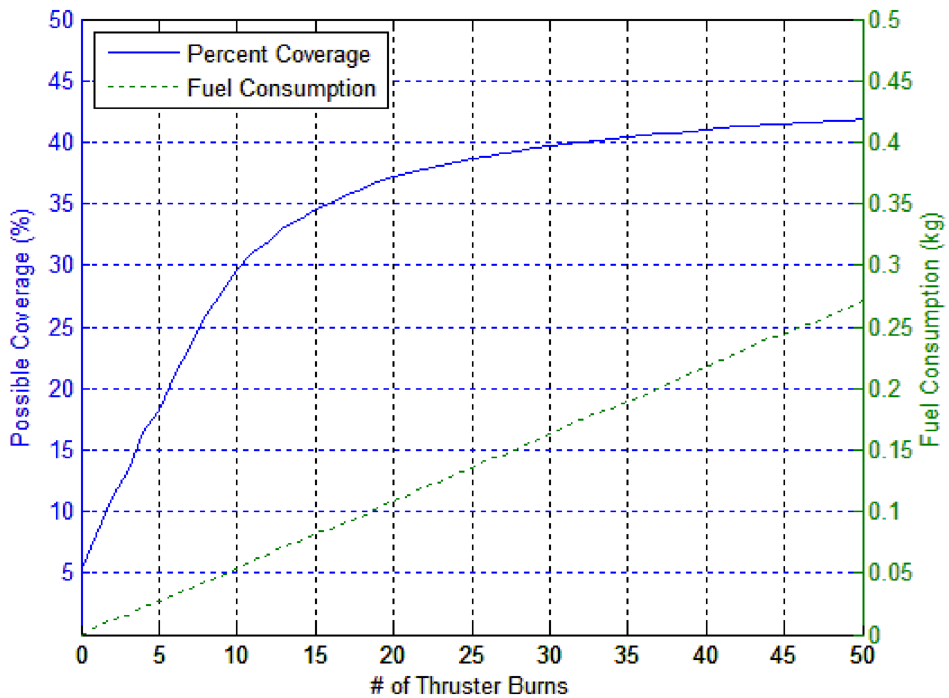

Figure 4.25 Availability of Target for Access and Fuel Consumption Using Thruster 5

4.3 Elliptical Orbit

Elliptical orbits were evaluated similarly to circular orbits. The satellite was thrusted continuously from perigee to apogee cumulatively from 1 to 50 times and coverage was assessed. The initial perigee altitude was set at 622 km and the initial apogee altitude was set at 18,622 km. This maneuver was accomplished at inclinations ranging from 40 to 90 degrees. The argument of perigee was initially established at 90 degrees for each inclination. While a range of inclinations was evaluated, the significant results occur at the extremes. For this reason, only data from the 40 and 90 degree inclinations is discussed below.

Additionally, the elliptical orbit was evaluated using a maneuver to alter the RAAN. As the satellite was ascending from apogee to perigee, continuous thrust was applied in a direction normal to the velocity vector. On the descent back to apogee, continuous thrust was applied in the opposite direction. The maneuver was also reversed to thrust anti-normally and then normally from perigee to apogee.

Figure 3.2 shows the reference vectors. The x-axis is aligned with the velocity vector. The z-axis is directed towards nadir. Finally, the y-axis is aligned with the vector normal to the orbital plane. For the purpose of this discussion, when thrust is directed “normally” the delta-v is in the positive y-axis direction. Conversely, when thrust is directed “anti-normally” the delta-v is in the negative y-axis direction.

4.3.1. Eccentricity Manipulation

Below are the charts showing the total coverage and fuel usage for the elliptical orbits. It should be noted that access for the duration of the period was limited only to access within the vicinity of perigee. By design, perigee occurs at the peak in inclination. For example, at 40

degrees inclination, the perigee will occur at 40 degrees latitude. Similarly, for the polar orbit, the altitude for each access will be higher as perigee will actually occur over the North Pole.

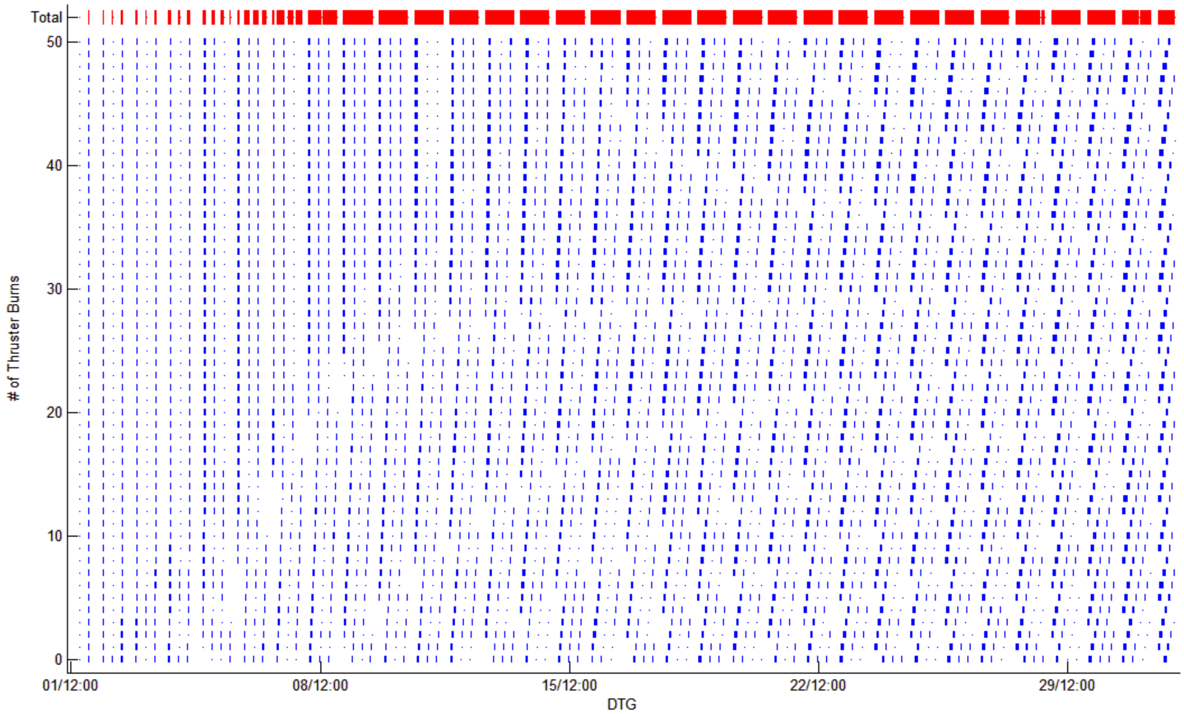

Figure 4.26 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 1

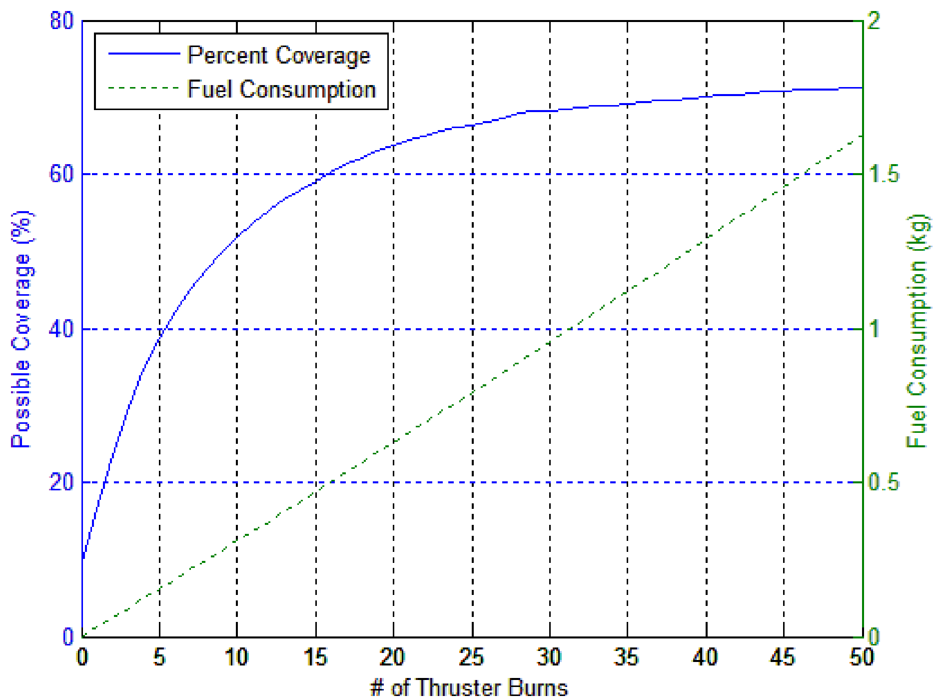

Figure 4.27 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 1

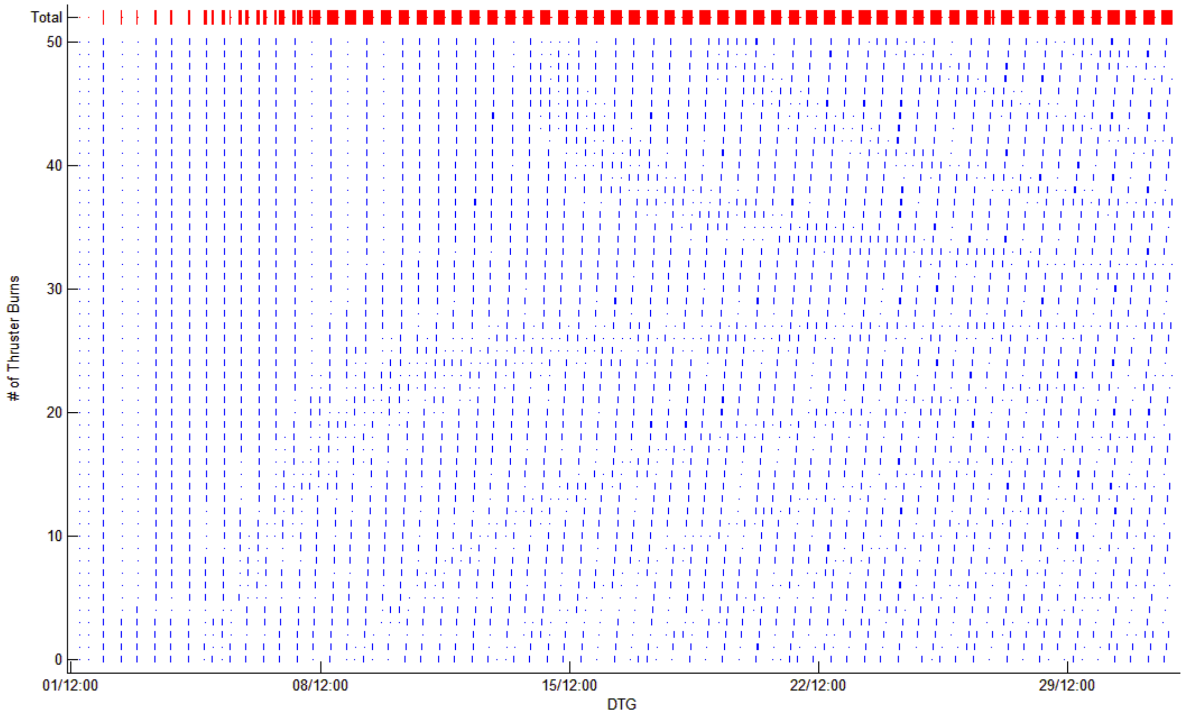

Figure 4.28 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 1

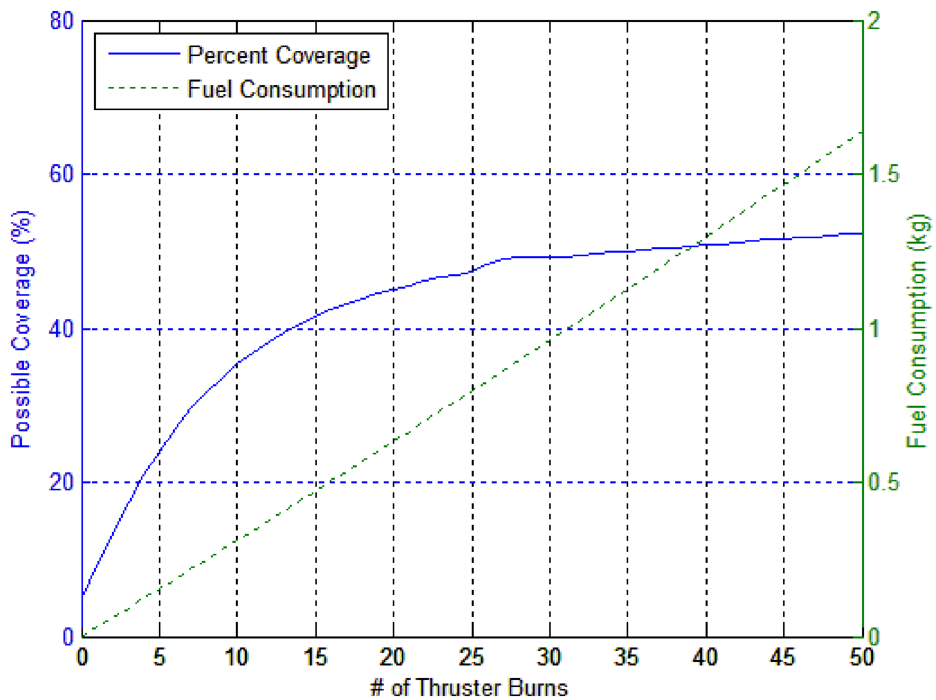

Figure 4.29 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 1

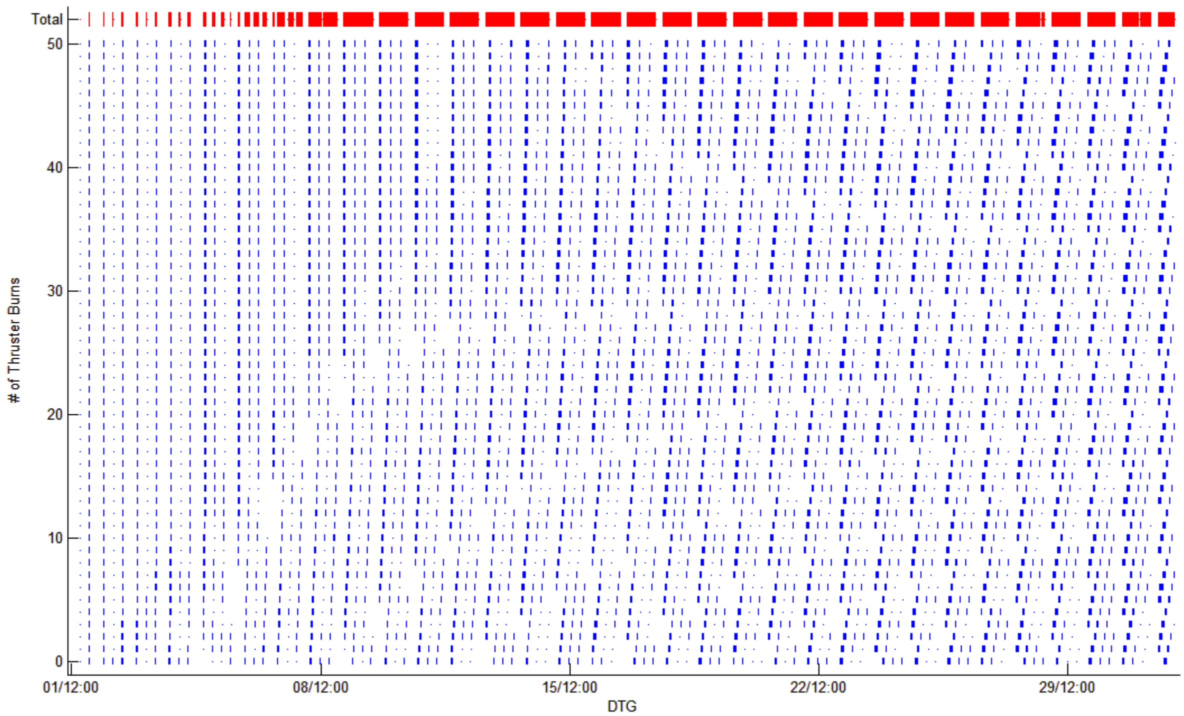

Figure 4.30 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 5

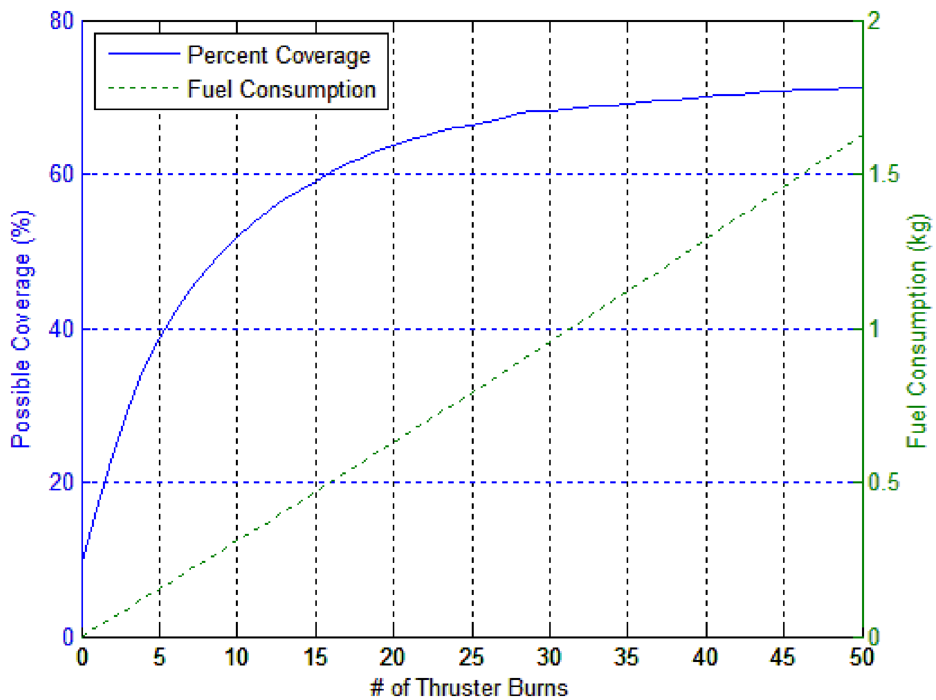

Figure 4.31 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 5

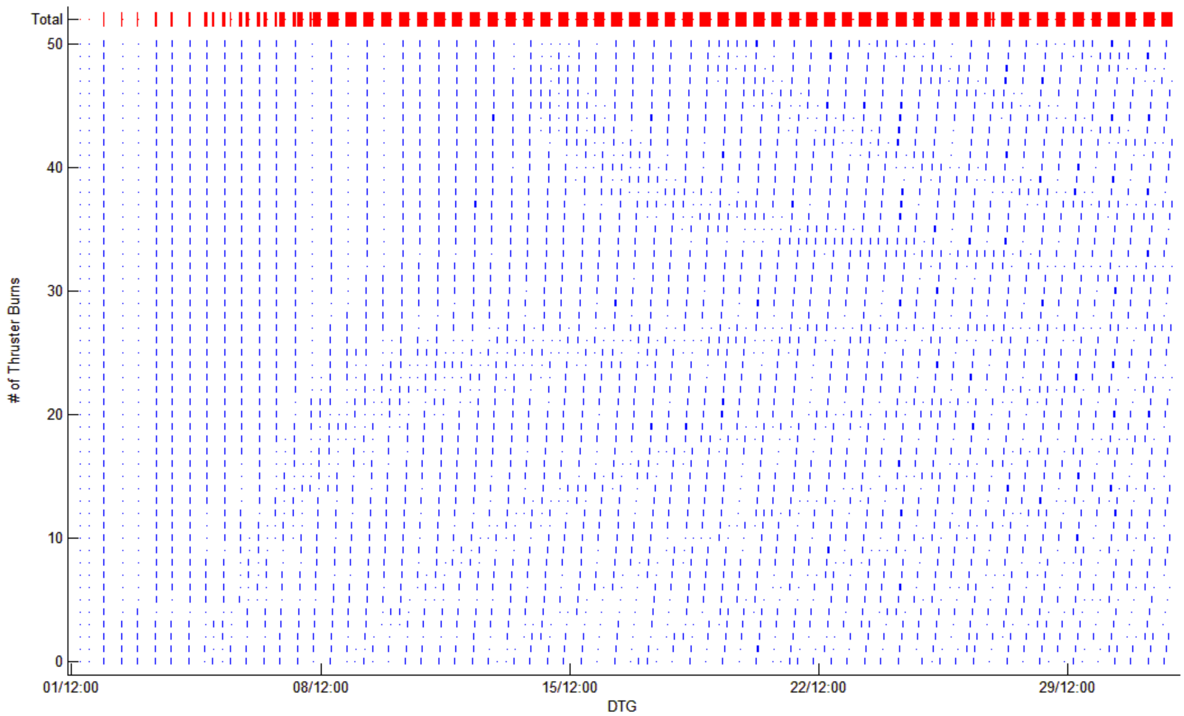

Figure 4.32 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 5

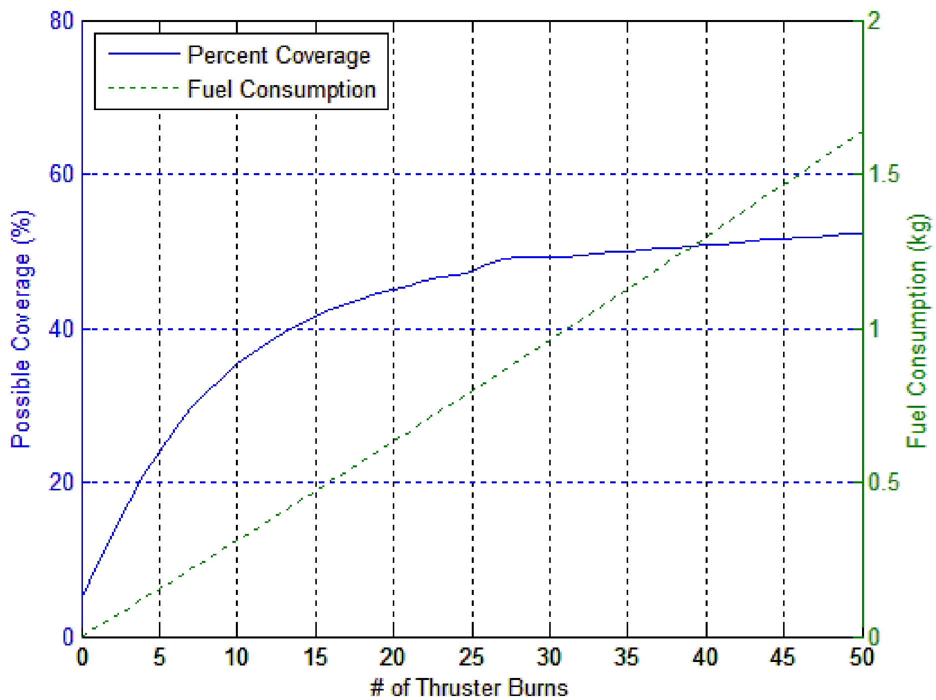

Figure 4.33 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 5

Significant coverage results are obtained using this method. Regardless of the thruster used, nearly 70% potential coverage is possible. However, 40 degree inclination is much more efficient at attaining coverage. At 40 maneuvers, the lower inclination offers nearly 70% percent coverage while the similarly thrusted 90 degree inclination scenario has only attained 50% coverage. In fact, the less inclined scenario resulted in the majority of coverage gains in the first 20 maneuvers attaining nearly 65% coverage.

The much greater eccentricity and period seems to overcome the problems noted with the circular orbit and regression of the ascending node generating a much larger window of opportunity for access. As can be seen in the total coverage for each scenario, the bands where access is limited are much narrower.

4.3.2. RAAN Manipulation

To evaluate manipulation of the ascending node, maneuvers were attempted to both enhance and limit the regression. By thrusting normally to the orbital plane (or anti-normally) from perigee to apogee and then anti-normally (or normally) from apogee to perigee, the RAAN was altered. The thrust likely did very little while it was close to perigee. However, at the slower velocities found at apogee, the effect was more significant.

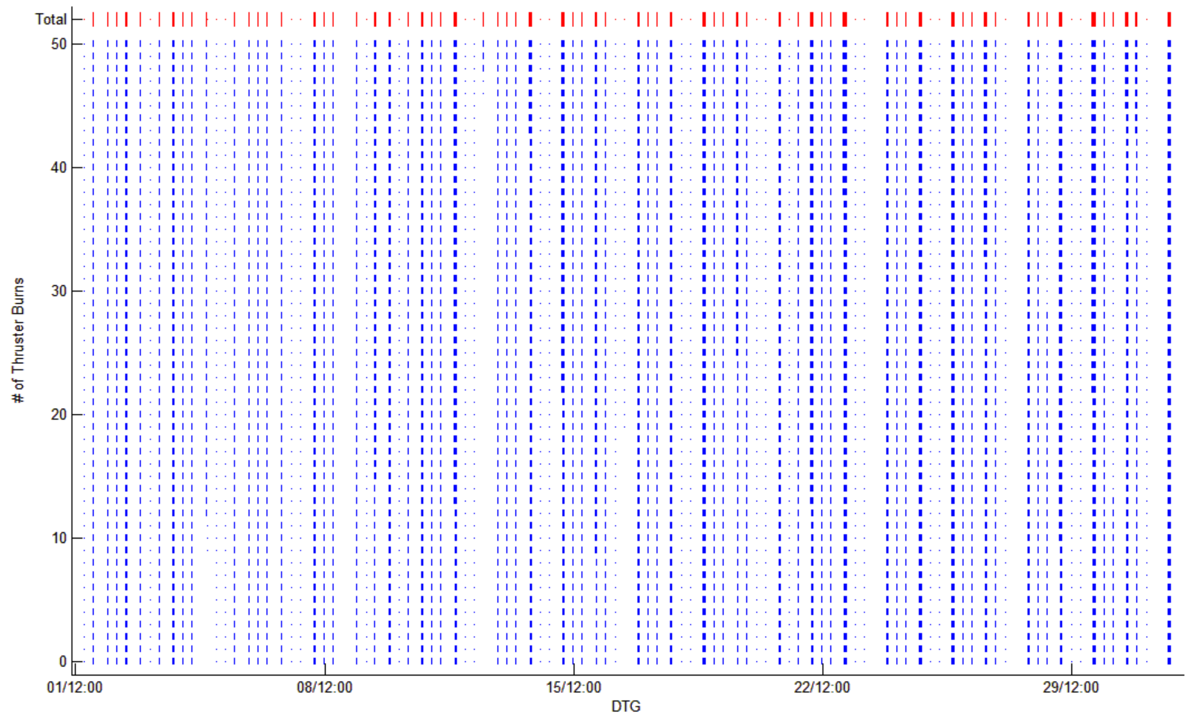

Figure 4.34 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 1 (Thrusting Normal then Anti-Normal)

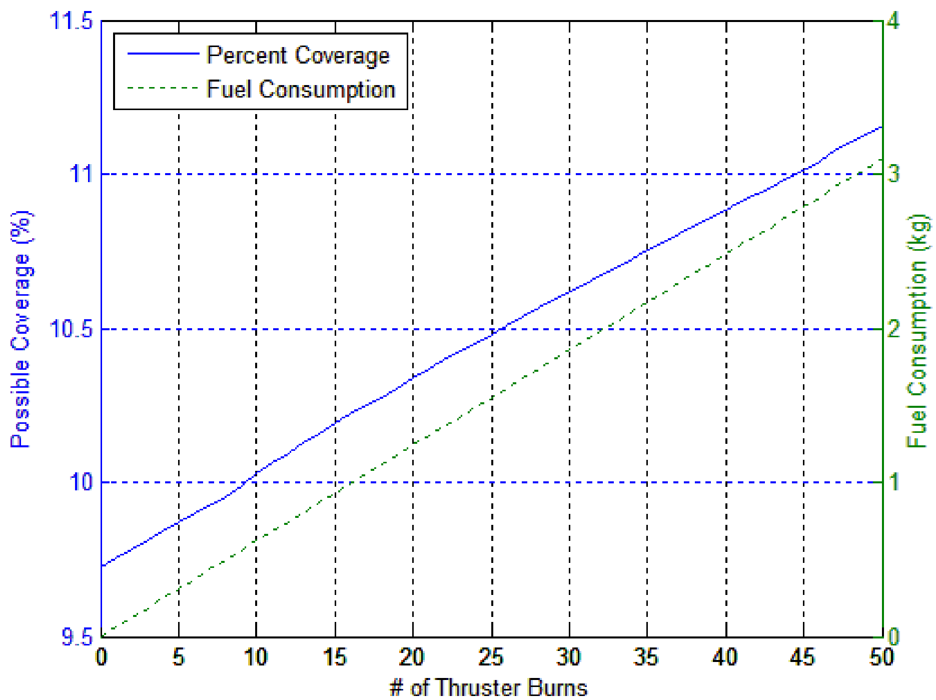

Figure 4.35 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 1 (Thrusting Normal then Anti-Normal)

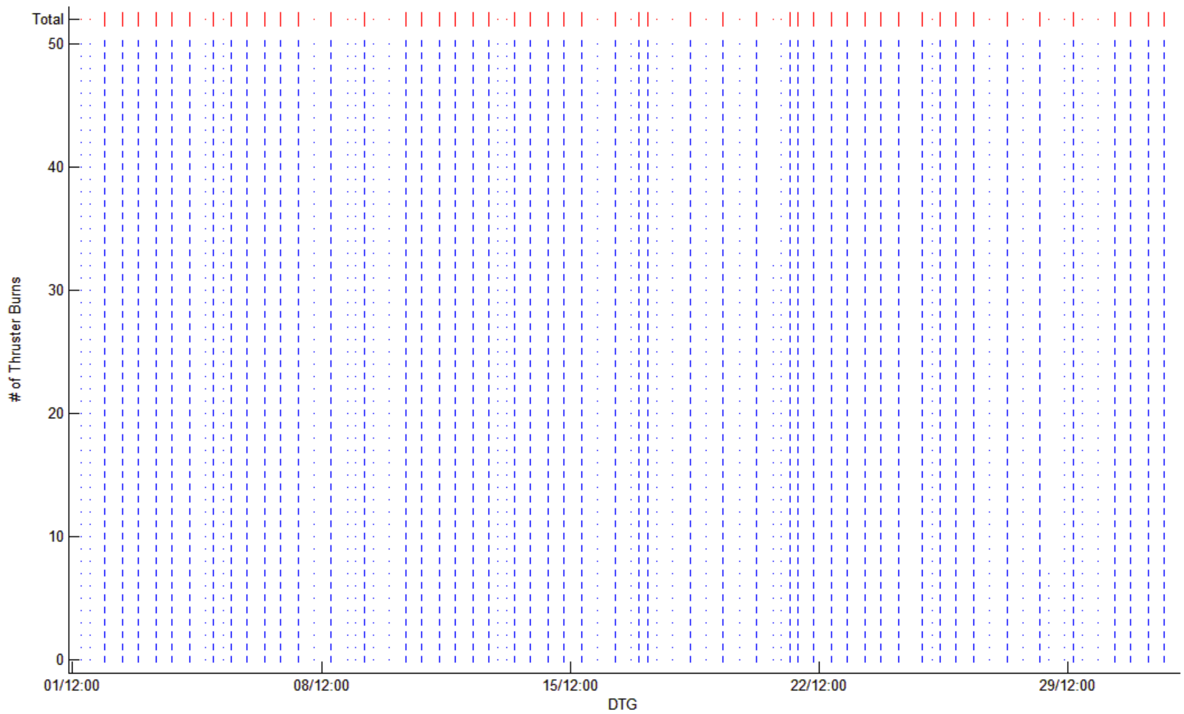

Figure 4.36 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 1 (Thrusting Normal then Anti-Normal)

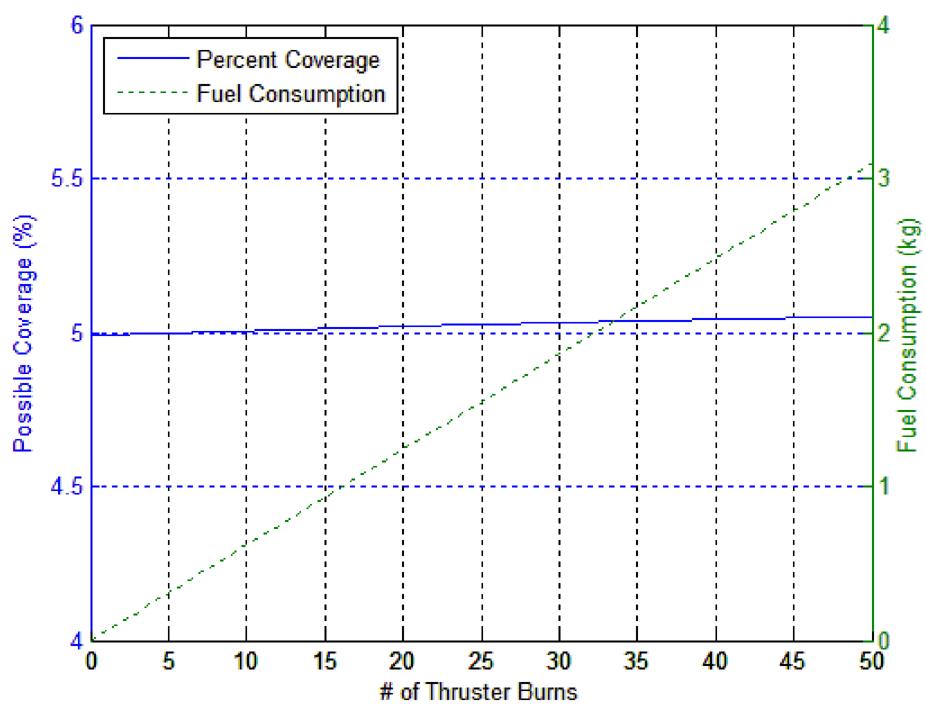

Figure 4.37 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 1 (Thrusting Normal then Anti-Normal)

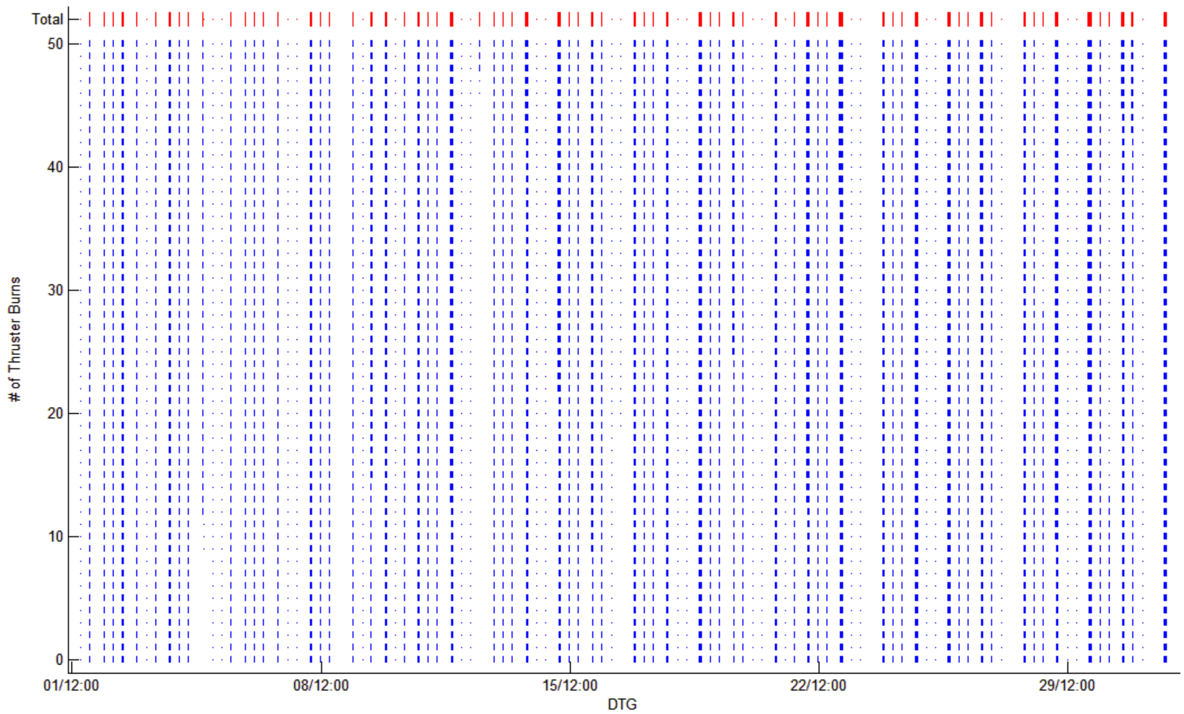

Figure 4.38 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 5 (Thrusting Normal then Anti-Normal)

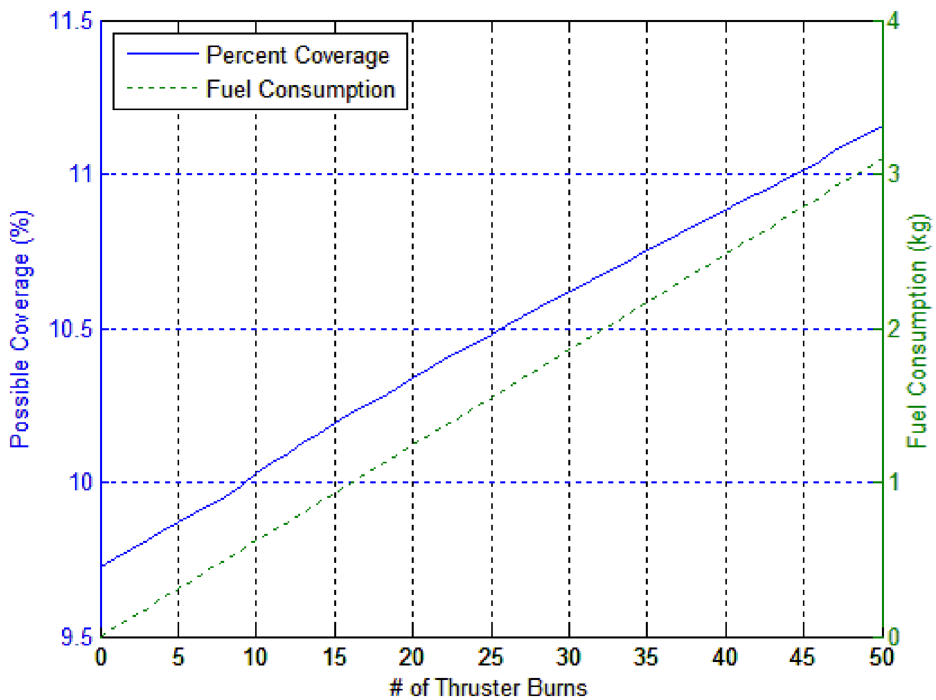

Figure 4.39 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 5 (Thrusting Normal then Anti-Normal)

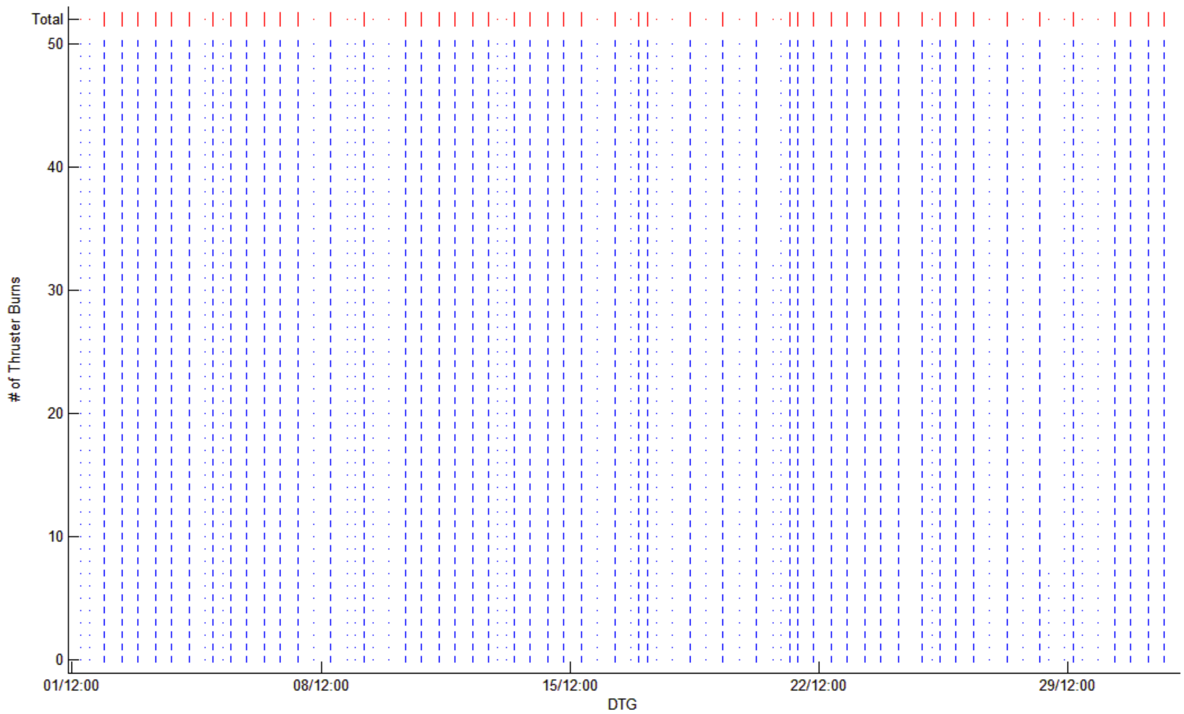

Figure 4.40 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 5 (Thrusting Normal then Anti-Normal)

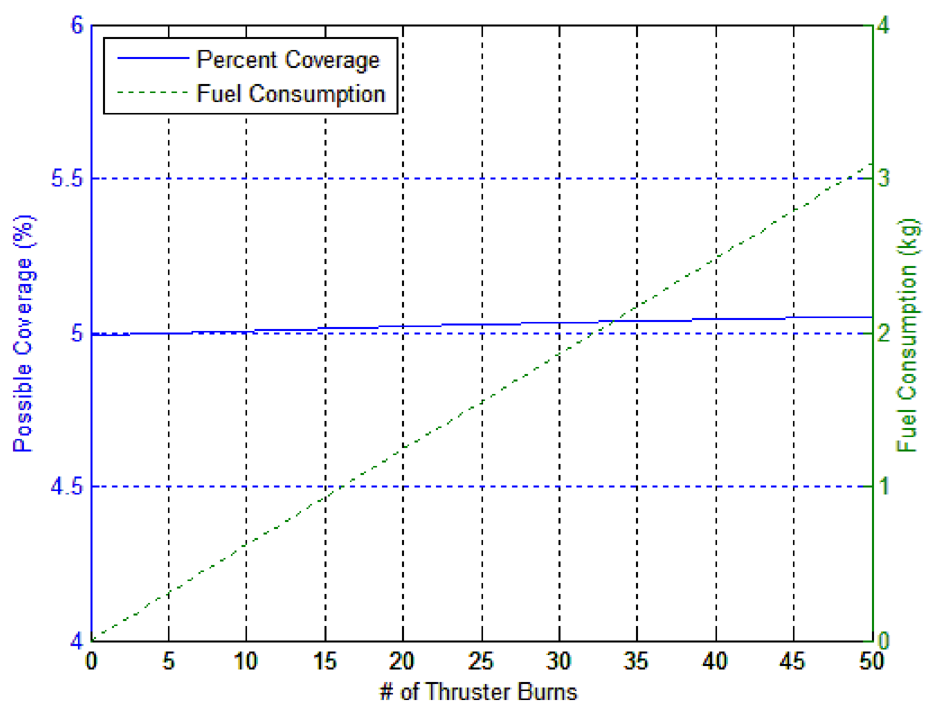

Figure 4.41 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 5 (Thrusting Normal then Anti-Normal)

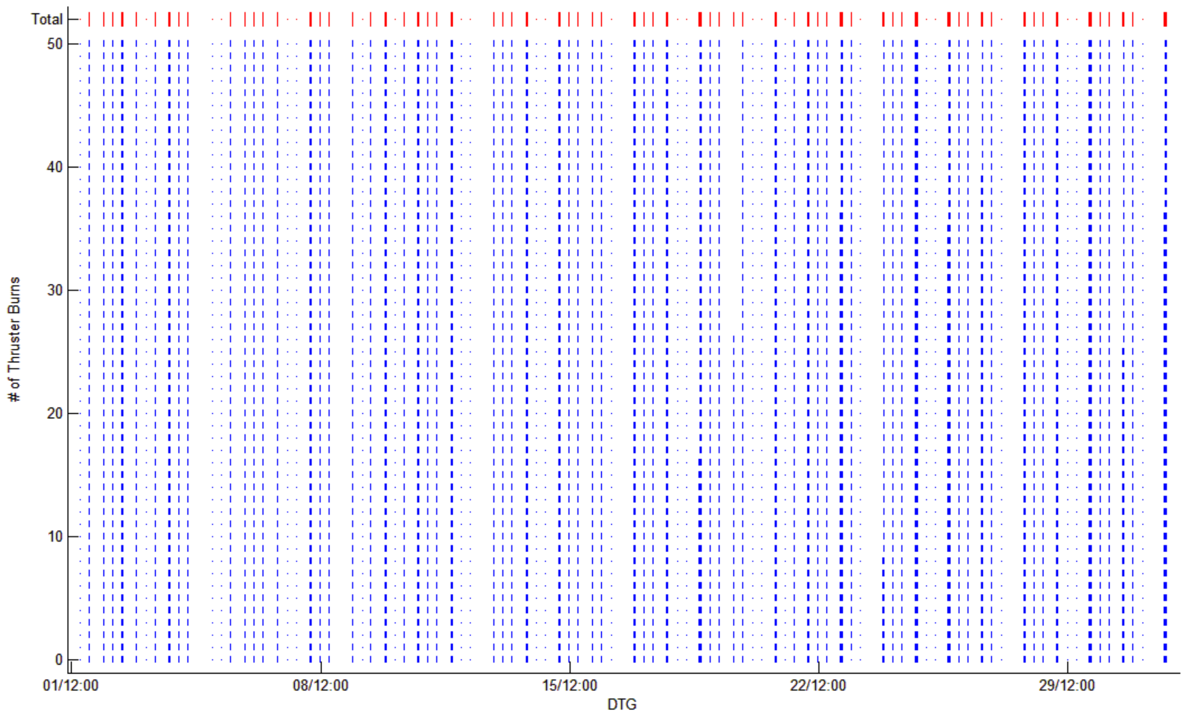

Figure 4.42 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 1 (Thrusting Anti-Normal then Normal)

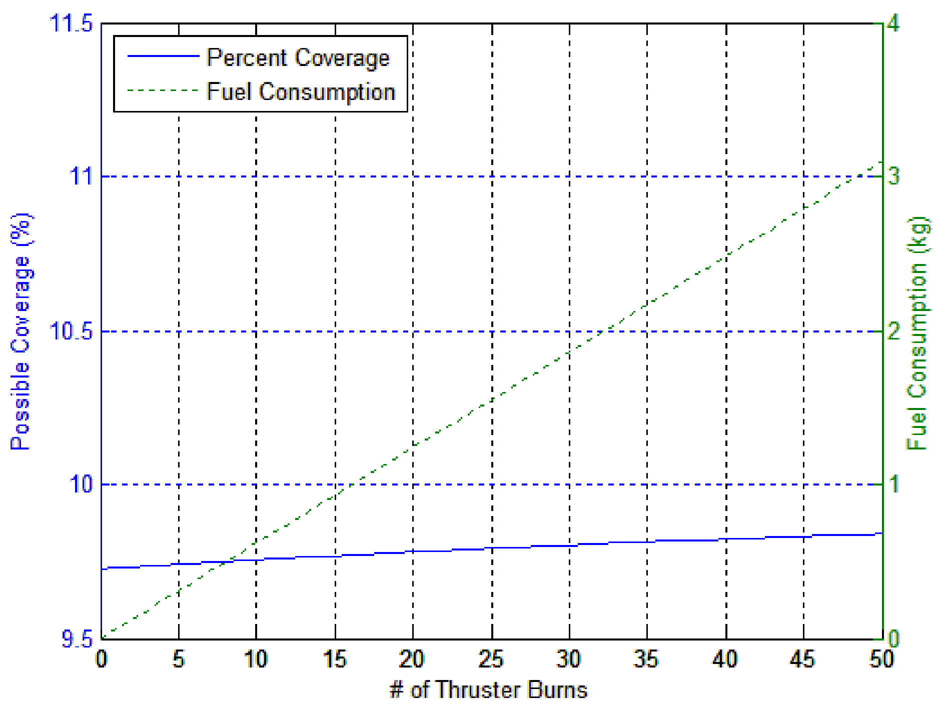

Figure 4.43 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 1 (Thrusting Anti-Normal then Normal)

Figure 4.44 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 1 (Thrusting Anti-Normal then Normal)

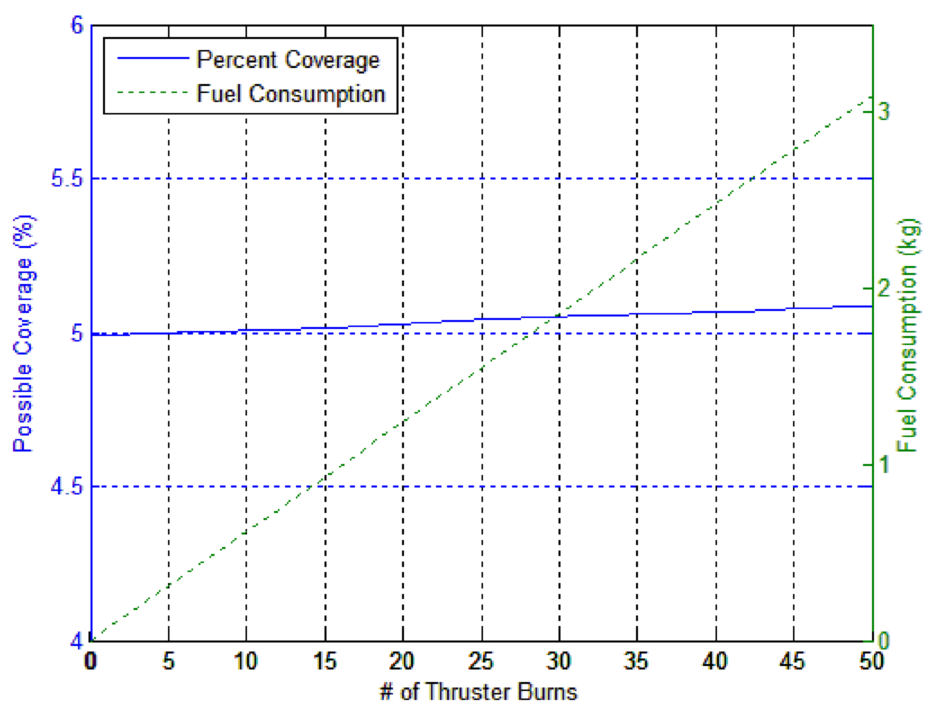

Figure 4.45 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 1 (Thrusting Anti-Normal then Normal)

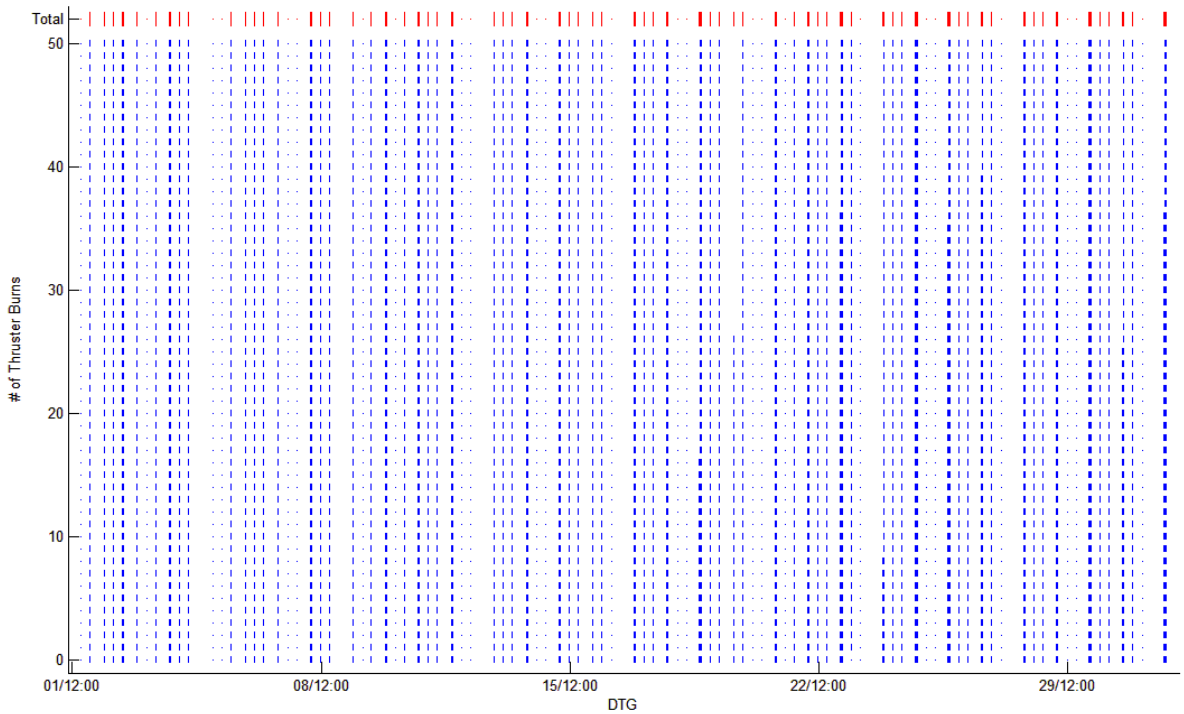

Figure 4.46 Target Access Bands for 30 Day Period at 40 deg Inclination Using Thruster 5 (Thrusting Anti-Normal then Normal)

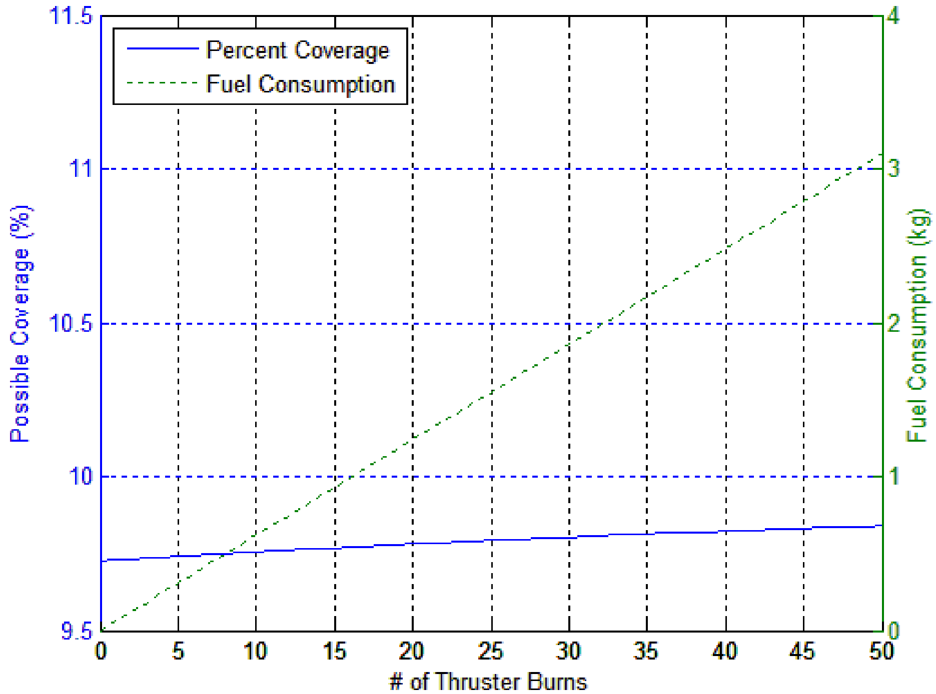

Figure 4.47 Availability of Target for Access and Fuel Consumption at 40 deg Inclination Using Thruster 5 (Thrusting Anti-Normal then Normal)

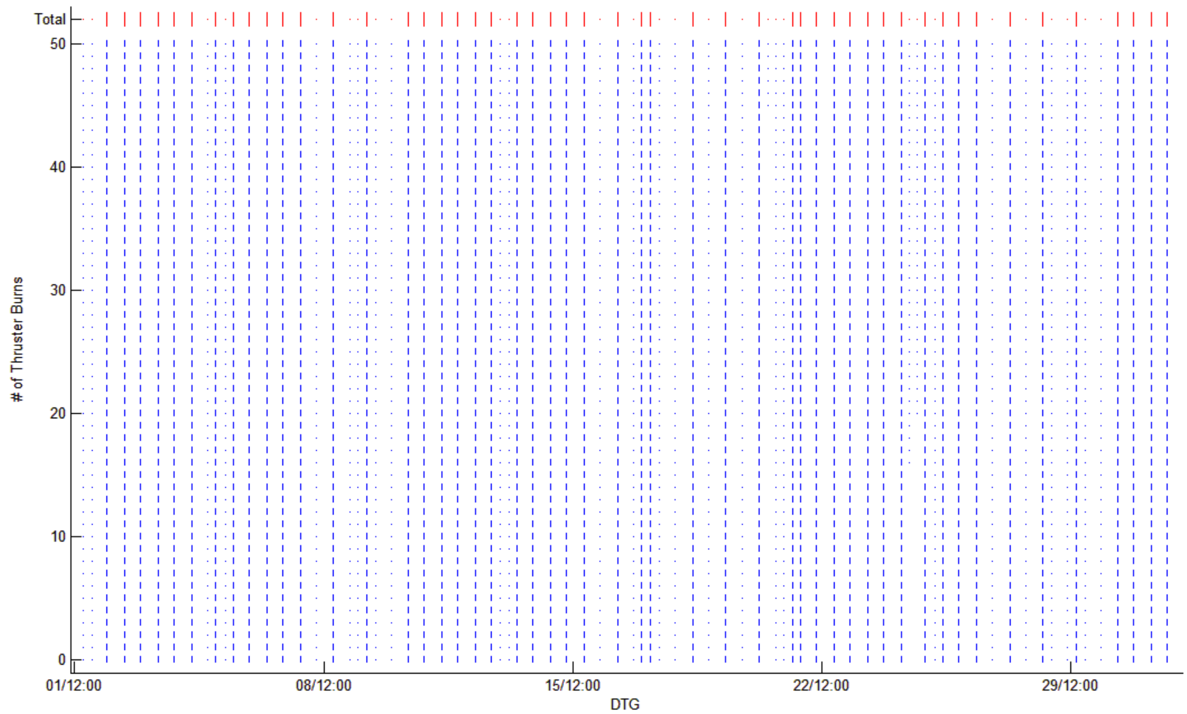

Figure 4.48 Target Access Bands for 30 Day Period at 90 deg Inclination Using Thruster 5 (Thrusting Anti-Normal then Normal)

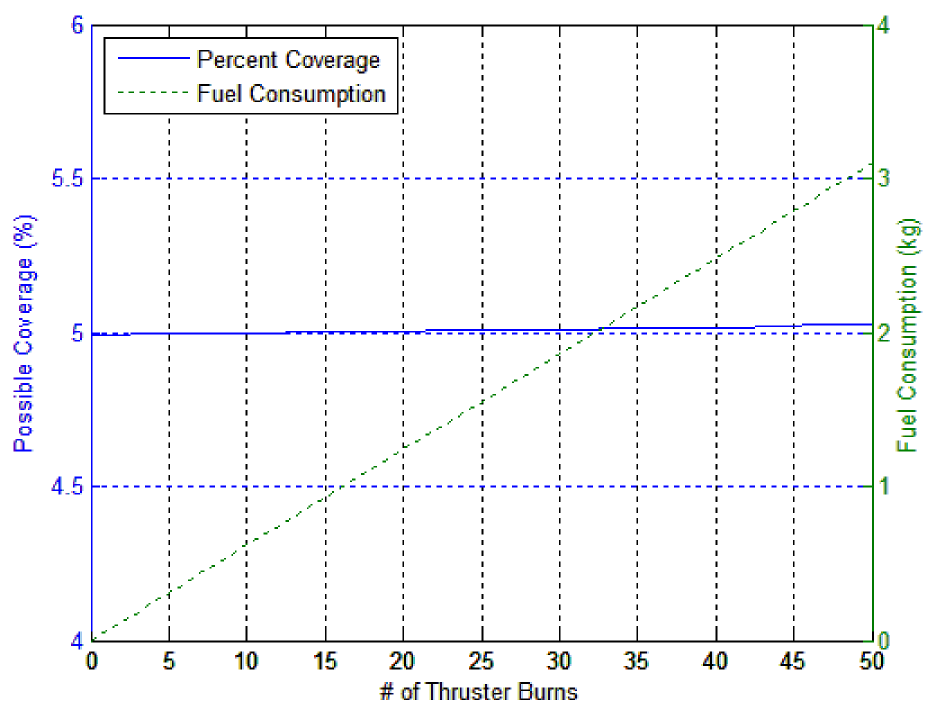

Figure 4.49 Availability of Target for Access and Fuel Consumption at 90 deg Inclination Using Thruster 5 (Thrusting Anti-Normal then Normal)

When using the normal anti-normal sequence, at 40 degrees inclination, the normal regression of the node was enhanced. Using the same sequence at 90 degrees induced a regression of the node. As would be expected, the node remained static once thrust was terminated. Alternately, when the anti-normal normal sequence was initiated at 40 degrees inclination, the regression was slowed. However, once thrust was terminated, the normal rate resumed. Finally, at 90 degrees inclination, the node advanced slightly and then remained static following completion of the maneuver.

Manipulation of the RAAN, while possible, revealed only very slight improvements to coverage. At 40 degrees inclination, un-thrusted coverage is only slightly below 10%. Following the sequence of maneuvers, the coverage improves only by about 0.2% when thrusted in the normal anti-normal sequence and about 1.5% when thrusted in the anti-normal normal sequence. At 90 degrees inclination, un-thrusted coverage is steady at 5%.

While some slight variation is noted based upon the thruster, the impact is minimal. Unfortunately, this maneuver appears outside the capabilities of electric propulsion. However, as was discussed previously, research has been conducted using alteration of the period and allowing for natural regression of the node. This method is not likely to be very responsive as it will require the eccentricity change and the natural regression taking a significant amount of time, depending on the amount of regression needed.

Finally, Chapter 5 will discuss the conclusions made with this research and identify recommendations for further research.

5. Conclusions & Recommendations

Manipulation of satellite orbits to achieve a responsive mission profile is well within the grasp of current technology. Using currently-available electric thruster technology, manipulation of several different orbits has been demonstrated. Low perigee orbits offer a unique opportunity for scientific and government mission requiring sub-ionospheric access. While such missions are possible with current technology, advances in thruster efficiency and power will likely improve the utility of such a maneuver.

Low perigee orbits, with current technology, will require a very eccentric orbit initially. A 60 mN thruster must have an initial apogee above 14,622 km to sustain orbit. Conversely, a 150 mN thruster requires an initial apogee above 4,622 km sustain orbit. While resulting in a very short mission profile, the 60 mN thruster was capable of supporting the satellite during analysis period with as little as 2200 km of apogee altitude. Additionally, improvements in power generation on spacecraft will allow for larger thrusters or multiple thruster configurations greatly enhancing thrust potential.

Additionally, the thrust profiles for low perigee orbit must be reevaluated. Thrusting from perigee to apogee inevitably raised the perigee. By raising the perigee, the satellite was no longer at the desired perigee and it was no longer experiencing the high drag encountered at low perigee. A thrust cycle centered at a different point in the orbital period and complex thrust angles warrant further consideration.

To achieve optimal coverage, a couple of general inferences are possible. The greatest potential for using electric propulsion to achieve responsive coverage exists in the highly-elliptical orbit with the argument of perigee matched with the latitude of the desired target. Given a lead time of 6 days or more, a scheduled access is possible 70%

of the time at a relatively low fuel cost. This level of access is not necessarily dependent upon thruster technology. Current technology can support this type of mission. However, improvements in thruster efficiency can greatly extend the lifetime of such missions.

A circular orbit, however, does offer potential benefits from continuous thrust and may be more responsive due to the shorter orbital period. With only 30 hours lead time, 30% potential coverage is possible. This only requires 20 thrust maneuvers and minimal fuel usage regardless of the thruster.

Manipulation of the ascending node, however, is outside the capabilities of current and near term electric propulsion methods. The delta-v required for such a maneuver remains best suited to traditional impulsive propulsion.

Each of the discussed orbital scenarios deserves further study. The infinite nature of space allows for an unimaginable number of possible scenarios. This analysis considered only a few of the most likely candidates. Additionally, while feasibility was demonstrated, scheduling specific access was not studied. In order for responsive maneuver to become a reality, an algorithm to determine the appropriate maneuver to achieve the access must be developed.

Ultimately, the object of additional research should focus on merging these two orbital concepts together. Low perigee orbit has significant potential for remote sensing. To truly recognize the benefits of low perigee orbit, however, the mission must be responsive to the user's needs. The asset must be taskable to provide that low altitude access at a specific future point in time.

Analysis was based upon a notional period with relatively nominal solar activity. Solar storming will greatly affect the performance of any low Earth orbit satellite. The effect of solar activity on low perigee orbits warrants further investigation.

Only access between the satellite and target was considered. Lighting requirements over the target would significantly limit the access. Additionally, if imaging was a primary objective, the different pass times could create difficulty where analysis is typically accomplished comparing similarly lighted images to determine changes.

This analysis also greatly simplified thruster performance to ease modeling requirements. In reality, thrusters can be throttled and fuel conserved. The likelihood of using a discrete "all or nothing" propulsion is neither efficient nor realistic. Complex thrust angles could be used to alter the regression of argument of perigee while manipulating the eccentricity of the orbit.

Clearly, while drastic manipulation of the ascending node is outside of the capabilities electric propulsion, the ascending node does affect coverage. Further research may reveal an optimum eccentricity and ascending node to provide optimal coverage of a target. Furthermore, electric propulsion may afford the opportunity to slow the regression and give a much greater opportunity for access.

Finally, this analysis also broadly assumed that the technology is available for such missions. However, radiation, drag, heat, and solar input are important variables for any spacecraft. A mission of this nature would require a highly specialized spacecraft that currently does not exist.

This thesis should function as a starting point for further research in responsive orbits. The technology is already available for responsive space missions and with the use of computer simulation, mission profiles similar to those documented here can be further analyzed and refined with the ultimate goal of fielding a space asset that is operationally taskable.

Appendix A. MATLAB Code

The following MATLAB code sequences were used to manipulate scenarios in STK as well as to collect data from the reports generated by each scenario. Explanations for each file are offered in the comments.

2/11/10 10:00 AM I:\My Documents\Thesis\Move\STK_initialization.m 1 of 1

```
% Timothy Hall
% STK Initialization Code
% Must be run with STK already open.

close all
clear all
clc



agiInit% run when first starting up
stkInit
conid=stkOpen
```

```
% Timothy Hall
% MATLAB Astrogator Connect Command Sequence for circular orbit

clc

for j=1:5; %Thruster engine models 1:5
stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.segmentList.↙
Sequence.SegmentList.Maneuver1.FiniteMnvr.EngineModel Thruster_' num2str(j)]));
        for i=1:50;  %thrust repititions 1:50
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Initial_State.InitialState.Keplerian.PeriapsisAltSize 622 km');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Initial_State.InitialState.Keplerian.ApoapsisAltSize 623 km');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Initial_State.InitialState.Keplerian.w 90 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Initial_State.InitialState.Keplerian.RAAN 0 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Initial_State.InitialState.Keplerian.TA 0 deg');
            stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.↙
SegmentList.Sequence.repeatcount ' num2str(i)]));
            stkExec(conid, 'Astrogator */Satellite/Satellite1 RunMCS');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Save Style↙
"Access" File "C:\Users\Tim\Documents\MATLAB\Thesis\circle\data\CT' num2str(j) 'B' num2str↙
(i) '.txt" AccessObject */Facility/Dayton']));
            stkExec(conid, 'ExportConfig / Connection Delimiter comma Headers none ');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style↙
"Access" File "C:\Users\Tim\Documents\MATLAB\Thesis\circle\data\CT' num2str(j) 'B' num2str↙
(i) '.csv" AccessObject */Facility/Dayton']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style↙
"ManeuverData" File "C:\Users\Tim\Documents\MATLAB\Thesis\circle\data\CT' num2str(j) 'B'↙
num2str(i) 'summary.txt"']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style↙
"ParamData" File "C:\Users\Tim\Documents\MATLAB\Thesis\circle\data\CT' num2str(j) 'B'↙
num2str(i) 'paramdata.txt"']));
        end
end
```

```
% Timothy Hall
% MATLAB Astrogator Connect Command Sequence for elliptical orbit
% (semi-major axis manipulation)

clc

for j=1:5; %Thruster engine models 1:5
stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.segmentList.
Sequence.SegmentList.Maneuver.FiniteMnvr.EngineModel Thruster_' num2str(j)]));
    for k=40:10:90; %inclination angles 40:10:90
        for i=1:50;  %thrust repititions 10:10:50
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.ApoapsisAltSize 18622 km');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.w 90 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.RAAN 0 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.TA 0 deg');
            stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.inc ' num2str(k) ' deg']));
            stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Sequence.repeatcount ' num2str(i)]));
            stkExec(conid, 'Astrogator */Satellite/Satellite1 RunMCS');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Save Style
"Access" File "C:\Users\Tim\Documents\MATLAB\Thesis\eccentric\data\E2T' num2str(j) 'B'
num2str(i) 'I' num2str(k) '.txt" AccessObject */Facility/Dayton']));
            stkExec(conid, 'ExportConfig / Connection Delimiter comma Headers none ');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"Access" File "C:\Users\Tim\Documents\MATLAB\Thesis\eccentric\data\E2T' num2str(j) 'B'
num2str(i) 'I' num2str(k) '.csv" AccessObject */Facility/Dayton']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"ManeuverData" File "C:\Users\Tim\Documents\MATLAB\Thesis\eccentric\data\E2T' num2str(j) 'B'
num2str(i) 'I' num2str(k)  'summary.txt"']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"ParamData" File "C:\Users\Tim\Documents\MATLAB\Thesis\eccentric\data\E2T' num2str(j) 'B'
num2str(i) 'I' num2str(k)  'paramdata.txt"']));
        end
    end
end
```

```
% Timothy Hall
% MATLAB Astrogator Connect Command Sequence for elliptical orbit
% (RAAN manipulation)

clc

for j=1:5; %Thruster engine models 1:5
stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.segmentList.
Sequence.SegmentList.Maneuver1.FiniteMnvr.EngineModel Thruster_' num2str(j)]));
stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.segmentList.
Sequence.SegmentList.Maneuver.FiniteMnvr.EngineModel Thruster_' num2str(j)]));
    for k=40:10:90; %inclination angles 40:10:90
        for i=1:50;  %thrust repititions 1:10:50
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.ApoapsisAltSize 18622 km');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.w 90 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.RAAN 0 deg');
            stkExec(conid, 'Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.TA 0 deg');
            stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Initial_State.InitialState.Keplerian.inc ' num2str(k) ' deg']));
            stkExec(conid, strcat(['Astrogator */Satellite/Satellite1 SetValue MainSequence.
SegmentList.Sequence.repeatcount ' num2str(i)]));
            stkExec(conid, 'Astrogator */Satellite/Satellite1 RunMCS');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Save Style
"Access" File "C:
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\data\E3T' num2str(j) 'B'
num2str(i) 'I' num2str(k) '.txt" AccessObject */Facility/Dayton']));
            stkExec(conid, 'ExportConfig / Connection Delimiter comma Headers none ');
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"Access" File "C:
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\data\E3T' num2str(j) 'B'
num2str(i) 'I' num2str(k) '.csv" AccessObject */Facility/Dayton']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"ManeuverData" File "C:
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\data\E3T' num2str(j) 'B'
num2str(i) 'I' num2str(k)  'summary.txt"']));
            stkExec(conid, strcat(['ReportCreate */Satellite/Satellite1 Type Export Style
"ParamData" File "C:
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\data\E3T' num2str(j) 'B'
num2str(i) 'I' num2str(k)  'paramdata.txt"']));
        end
    end
end
```

```
% Timothy Hall
% Semi-major axis manipulation for circular orbit
% This MATLAB code plots the temporal coverage bands for each thrust.
% At the top of the plot, the overlapping coverages are shown in red.
% Additionally, the fuel useage will be plotted along with percent
% coverage.

close all
clear all
clc

addpath('C:\Users\Tim\Documents\MATLAB\Thesis\circle\data\')

    for j=1:5; %thruster
        close all
        clear('data','cover*')
        figure('Position',[1 1 1280 800])
        hold on
        for i=1:51; %num of thrusts
            clear dtg
            filename=strcat(['CT' num2str(j) 'B' num2str(i-1) '.csv']);
            data=importdata(filename);
            dtg(1:length(data.textdata(:,2)),1)=datenum(data.textdata(1:length(data.textdata↙
(:,2)),2),'dd mmm yyyy HH:MM:SS.FFF')';
            dtg(1:length(data.textdata(:,3)),2)=datenum(data.textdata(1:length(data.textdata↙
(:,3)),3),'dd mmm yyyy HH:MM:SS.FFF')';
            startdate=datenum(2007,08,01,12,00,00);
            enddate=datenum(2007,09,01,12,00,00);

            limit=sum(dtg(:,1)<=enddate);
            for m=1:limit;
                plot([dtg(m,1) dtg(m,2)],[i-1 i-1],'-b','LineWidth',5)
                plot([dtg(m,1) dtg(m,2)],[52 52],'-r','LineWidth',10)
            end

            if i==1;
                cover(:,:,1)=dtg(:,:);
            else
                cover(:,:,i)=cover(:,:,i-1);
                L=length(cover(:,:,i));
                L2=length(dtg(:,1));
                cover(L+1:L+L2,:,i)=dtg(:,:);
            end
            cover(:,:,i)=sortrows(cover(:,:,i));
        end
        xlabel('DTG')
        ylabel('# of Thruster Burns')
        set(gca,'XTick',startdate:7:enddate)
        set(gca,'XTickLabel',datestr(startdate:7:enddate,'dd/HH:MM'))
        set(gca,'Ytick',[0:10:50 52])
        set(gca,'YTickLabel',{'0','10','20','30','40','50', 'Total'})
        axis([startdate-1/8 enddate+1/8 -1 53]);
```

```
        %%
        total=datenum(2007,09,01,12,00,00)-datenum(2007,08,01,12,00,00);

        for jjj=1:51;
            max=0;
            min=0;
            for kkk=1:length(cover(:,1,1))-1;
                if kkk==1
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,2,jjj)<=max
                    duration(kkk,jjj)=0;
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,1,jjj)>=max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    min=cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                elseif cover(kkk,1,jjj)<max&&cover(kkk,2,jjj)>max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-max;
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                end
             end
            sum_duration(jjj)=(sum(duration(:,jjj)))/total;
        end
        %%
        clear('fuel','data2')
        fuel(1)=0;
        for u=1:50;
            filename2=strcat(['CT' num2str(j) 'B' num2str(u) 'summary.txt']);
            data2=importdata(filename2);
            fuel(u+1)=sum(data2(:,2));
        end

        %%
        figure
        [AX,H1,H2]=plotyy(0:50,sum_duration*100,0:50,fuel);
        set(get(AX(1),'Ylabel'),'string','Possible Coverage (%)')
        set(get(AX(2),'Ylabel'),'string','Fuel Consumption (kg)')
        xlabel('# of Thruster Burns')
        set(H2,'LineStyle',':')
        legend('Percent Coverage','Fuel Consumption','location','NorthWest')
        grid on

        print(1, '-dbitmap', strcat(['C:\Users\Tim\Documents\MATLAB\Thesis\circle\plots\CT'
num2str(j) 'monthcov.bmp']))
        print(2, '-dbitmap', strcat(['C:\Users\Tim\Documents\MATLAB\Thesis\circle\plots\CT'
num2str(j) 'covandfuel.bmp']))
    end
```

```
% Timothy Hall
% Semi-major axis manipulation for eccentric orbit
% This MATLAB code plots the temporal coverage bands for each thrust.
% At the top of the plot, the overlapping coverages are shown in red.
% Additionally, the fuel useage will be plotted along with percent
% coverage.

close all
clear all
clc

addpath('C:\Users\Tim\Documents\MATLAB\Thesis\eccentric\data\')

for k=40:10:90; % inclination
    for j=1:5; %thruster
        close all
        clear('data','cover*')
        figure('Position',[1 1 1280 800])
        hold on
        for i=1:51; %num of thrusts
            clear dtg
            filename=strcat(['E2T' num2str(j) 'B' num2str(i-1) 'I' num2str(k) '.csv']);
            data=importdata(filename);
            dtg(1:length(data.textdata(:,2)),1)=datenum(data.textdata(1:length(data.textdata↙
(:,2)),2),'dd mmm yyyy HH:MM:SS.FFF')';
            dtg(1:length(data.textdata(:,3)),2)=datenum(data.textdata(1:length(data.textdata↙
(:,3)),3),'dd mmm yyyy HH:MM:SS.FFF')';
            startdate=datenum(2007,08,01,12,00,00);
            enddate=datenum(2007,09,01,12,00,00);

            limit=sum(dtg(:,1)<=enddate);
            for m=1:limit;
                plot([dtg(m,1) dtg(m,2)],[i-1 i-1],'-b','LineWidth',5)
                plot([dtg(m,1) dtg(m,2)],[52 52],'-r','LineWidth',10)
            end

            if i==1;
                cover(:,:,1)=dtg(:,:);
            else
                cover(:,:,i)=cover(:,:,i-1);
                L=length(cover(:,:,i));
                L2=length(dtg(:,1));
                cover(L+1:L+L2,:,i)=dtg(:,:);
            end
            cover(:,:,i)=sortrows(cover(:,:,i));
        end
        xlabel('DTG')
        ylabel('# of Thruster Burns')
        set(gca,'XTick',startdate:7:enddate)
        set(gca,'XTickLabel',datestr(startdate:7:enddate,'dd/HH:MM'))
        set(gca,'Ytick',[0:10:50 52])
        set(gca,'YTickLabel',{'0','10','20','30','40','50', 'Total'})
```

```
        axis([startdate-1/8 enddate+1/8 -1 53]);

        total=datenum(2007,09,01,12,00,00)-datenum(2007,08,01,12,00,00);
        for jjj=1:51;
            max=0;
            min=0;
            for kkk=1:length(cover(:,1,1))-1;
                if kkk==1
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,2,jjj)<=max
                    duration(kkk,jjj)=0;
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,1,jjj)>=max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    min=cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                elseif cover(kkk,1,jjj)<max&&cover(kkk,2,jjj)>max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-max;
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                end
            end
            sum_duration(jjj)=(sum(duration(:,jjj)))/total;
        end
        clear('fuel','data2')
        fuel(1)=0;
        for u=1:50;
            filename2=strcat(['E2T' num2str(j) 'B' num2str(u) 'I' num2str(k) 'summary.↙
txt']);
            data2=importdata(filename2);
            fuel(u+1)=sum(data2(:,2));
        end
        figure
        [AX,H1,H2]=plotyy(0:50,sum_duration*100,0:50,fuel);
        set(get(AX(1),'Ylabel'),'string','Possible Coverage (%)')
        set(get(AX(2),'Ylabel'),'string','Fuel Consumption (kg)')
        xlabel('# of Thruster Burns')
        set(H2,'LineStyle',':')
        legend('Percent Coverage','Fuel Consumption','location','NorthWest')
        grid on

        print(1, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\eccentric\plots\E2T' num2str(j) 'I' num2str(k) 'monthcov.↙
bmp']))
        print(2, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\eccentric\plots\E2T' num2str(j) 'I' num2str(k)↙
'covandfuel.bmp']))
    end
end
```

```
% Timothy Hall
% RAAN manipulation for eccentric orbit
% This MATLAB code plots the temporal coverage bands for each thrust.
% At the top of the plot, the overlapping coverages are shown in red.
% Additionally, the fuel useage will be plotted along with percent
% coverage.

close all
clear all
clc

addpath('C:\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\data\')
% addpath('C:\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\Normal_AntiNormal\data\')

for k=40:10:90; % inclination
    for j=1:5; %thruster
        close all
        clear('data','cover*')
        figure('Position',[1 1 1280 800])
        hold on
        for i=1:51; %num of thrusts
            clear dtg
            filename=strcat(['E3T' num2str(j) 'B' num2str(i-1) 'I' num2str(k) '.csv']);
            data=importdata(filename);
            dtg(1:length(data.textdata(:,2)),1)=datenum(data.textdata(1:length(data.textdata
(:,2)),2),'dd mmm yyyy HH:MM:SS.FFF')';
            dtg(1:length(data.textdata(:,3)),2)=datenum(data.textdata(1:length(data.textdata
(:,3)),3),'dd mmm yyyy HH:MM:SS.FFF')';
            startdate=datenum(2007,08,01,12,00,00);
            enddate=datenum(2007,09,01,12,00,00);

            limit=sum(dtg(:,1)<=enddate);
            for m=1:limit;
                plot([dtg(m,1) dtg(m,2)],[i-1 i-1],'-b','LineWidth',5)
                plot([dtg(m,1) dtg(m,2)],[52 52],'-r','LineWidth',10)
            end

            if i==1;
                cover(:,:,1)=dtg(:,:);
            else
                cover(:,:,i)=cover(:,:,i-1);
                L=length(cover(:,:,i));
                L2=length(dtg(:,1));
                cover(L+1:L+L2,:,i)=dtg(:,:);
            end
            cover(:,:,i)=sortrows(cover(:,:,i));
        end

        xlabel('DTG')
        ylabel('# of Thruster Burns')
        set(gca,'XTick',startdate:7:enddate)
        set(gca,'XTickLabel',datestr(startdate:7:enddate,'dd/HH:MM'))
```

```
        set(gca,'Ytick',[0:10:50 52])
        set(gca,'YTickLabel',{'0','10','20','30','40','50', 'Total'})
        axis([startdate-1/8 enddate+1/8 -1 53]);

        total=datenum(2007,09,01,12,00,00)-datenum(2007,08,01,12,00,00);
        for jjj=1:51;
            max=0;
            min=0;
            for kkk=1:length(cover(:,1,1))-1;
                if kkk==1
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,2,jjj)<=max
                    duration(kkk,jjj)=0;
                    min=cover(kkk,1,jjj);
                elseif cover(kkk,1,jjj)>=max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-cover(kkk,1,jjj);
                    min=cover(kkk,1,jjj);
                    max=cover(kkk,2,jjj);
                elseif cover(kkk,1,jjj)<max&&cover(kkk,2,jjj)>max
                    duration(kkk,jjj)=cover(kkk,2,jjj)-max;
                    max=cover(kkk,2,jjj);
                    min=cover(kkk,1,jjj);
                end
             end
            sum_duration(jjj)=(sum(duration(:,jjj)))/total;
        end

        clear('fuel','data2')
        fuel(1)=0;
        for u=1:50;
            filename2=strcat(['E3T' num2str(j) 'B' num2str(u) 'I' num2str(k) 'summary.↙
txt']);
            data2=importdata(filename2);
            fuel(u+1)=sum(data2(:,2));
        end

        figure
        [AX,H1,H2]=plotyy(0:50,sum_duration*100,0:50,fuel);
        set(get(AX(1),'Ylabel'),'string','Possible Coverage (%)')
        set(get(AX(2),'Ylabel'),'string','Fuel Consumption (kg)')
        xlabel('# of Thruster Burns')
        set(H2,'LineStyle',':')
        legend('Percent Coverage','Fuel Consumption','location','NorthWest')
        grid on

        print(1, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\plots\E3T' num2str(j) 'I'↙
num2str(k) 'monthcov.bmp']))
        print(2, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\AntiNormal_Normal\plots\E3T' num2str(j) 'I'↙
```

```
num2str(k) 'covandfuel.bmp']))
%         print(1, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\Normal_AntiNormal\plots\E3T' num2str(j) 'I'↙
num2str(k) 'monthcov.bmp']))
%         print(2, '-dbitmap', strcat(['C:↙
\Users\Tim\Documents\MATLAB\Thesis\RAANeccentric\Normal_AntiNormal\plots\E3T' num2str(j) 'I'↙
num2str(k) 'covandfuel.bmp']))
    end
end
```

Appendix B. Sample Data Report

Below is a sample data report showing the access periods for a circular orbit that was thrusted from perigee to apogee 50 times using the 5000 ISP/150 mN thruster.

Educational Use Only
Access Summary Report

Satellite1-To-Dayton

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Aug 2007 13:25:48.650	1 Aug 2007 13:39:45.567	836.917
2	1 Aug 2007 15:08:16.974	1 Aug 2007 15:22:19.025	842.052
3	1 Aug 2007 16:50:50.158	1 Aug 2007 17:04:41.819	831.661
4	1 Aug 2007 18:33:45.454	1 Aug 2007 18:45:48.320	722.866
5	2 Aug 2007 10:26:16.724	2 Aug 2007 10:38:10.687	713.963
6	2 Aug 2007 12:07:42.378	2 Aug 2007 12:21:52.189	849.811
7	2 Aug 2007 13:50:42.794	2 Aug 2007 14:05:11.866	869.072
8	2 Aug 2007 15:34:06.198	2 Aug 2007 15:48:35.474	869.276
9	2 Aug 2007 17:17:33.298	2 Aug 2007 17:31:20.554	827.256
10	2 Aug 2007 19:02:08.634	2 Aug 2007 19:11:52.214	583.580
11	3 Aug 2007 09:19:26.807	3 Aug 2007 09:29:11.373	584.566
12	3 Aug 2007 11:00:14.311	3 Aug 2007 11:14:13.408	839.097
13	3 Aug 2007 12:43:22.528	3 Aug 2007 12:58:07.890	885.362
14	3 Aug 2007 14:27:14.558	3 Aug 2007 14:42:02.079	887.521
15	3 Aug 2007 16:11:06.479	3 Aug 2007 16:25:37.535	871.055
16	3 Aug 2007 17:55:22.191	3 Aug 2007 18:07:42.999	740.808
17	4 Aug 2007 08:17:46.509	4 Aug 2007 08:21:56.755	250.246
18	4 Aug 2007 09:56:01.753	4 Aug 2007 10:09:03.880	782.126
19	4 Aug 2007 11:38:31.666	4 Aug 2007 11:53:09.372	877.706
20	4 Aug 2007 13:22:14.664	4 Aug 2007 13:37:02.128	887.463
21	4 Aug 2007 15:06:07.961	4 Aug 2007 15:20:51.060	883.099
22	4 Aug 2007 16:50:06.097	4 Aug 2007 17:03:42.540	816.443
23	4 Aug 2007 18:35:48.012	4 Aug 2007 18:43:36.347	468.335
24	5 Aug 2007 08:52:17.368	5 Aug 2007 09:03:37.226	679.859
25	5 Aug 2007 10:33:51.290	5 Aug 2007 10:48:09.687	858.397
26	5 Aug 2007 12:17:15.627	5 Aug 2007 12:32:02.132	886.505
27	5 Aug 2007 14:01:09.301	5 Aug 2007 14:15:56.140	886.838
28	5 Aug 2007 15:45:01.453	5 Aug 2007 15:59:18.949	857.496
29	5 Aug 2007 17:29:36.578	5 Aug 2007 17:40:47.816	671.239
30	6 Aug 2007 07:49:23.247	6 Aug 2007 07:57:30.524	487.276
31	6 Aug 2007 09:29:26.463	6 Aug 2007 09:43:05.266	818.803
32	6 Aug 2007 11:12:20.499	6 Aug 2007 11:27:02.996	882.498
33	6 Aug 2007 12:56:09.632	6 Aug 2007 13:10:56.836	887.204
34	6 Aug 2007 14:40:01.753	6 Aug 2007 14:54:39.155	877.402
35	6 Aug 2007 16:24:08.168	6 Aug 2007 16:37:05.770	777.602
36	6 Aug 2007 18:11:38.349	6 Aug 2007 18:14:55.729	197.380
37	7 Aug 2007 08:25:23.882	7 Aug 2007 08:37:49.862	745.981
38	7 Aug 2007 10:07:33.217	7 Aug 2007 10:22:03.953	870.735
39	7 Aug 2007 11:51:09.651	7 Aug 2007 12:05:56.270	886.618
40	7 Aug 2007 13:35:03.241	7 Aug 2007 13:49:48.275	885.034
41	7 Aug 2007 15:18:57.688	7 Aug 2007 15:32:54.334	836.646
42	7 Aug 2007 17:04:04.250	7 Aug 2007 17:13:34.838	570.588
43	8 Aug 2007 07:21:55.701	8 Aug 2007 07:32:10.845	615.144
44	8 Aug 2007 09:02:58.386	8 Aug 2007 09:17:02.545	844.158
45	8 Aug 2007 10:46:11.629	8 Aug 2007 11:00:56.258	884.629
46	8 Aug 2007 12:30:04.042	8 Aug 2007 12:44:50.712	886.671
47	8 Aug 2007 14:13:55.513	8 Aug 2007 14:28:22.992	867.479
48	8 Aug 2007 15:58:15.829	8 Aug 2007 16:10:18.566	722.737
49	9 Aug 2007 06:19:43.715	9 Aug 2007 06:25:25.359	341.644
50	9 Aug 2007 07:58:41.553	9 Aug 2007 08:11:54.292	792.739
51	9 Aug 2007 09:41:19.046	9 Aug 2007 09:55:57.022	877.976
52	9 Aug 2007 11:25:03.917	9 Aug 2007 11:39:50.219	886.302
53	9 Aug 2007 13:08:56.506	9 Aug 2007 13:23:37.684	881.179
54	9 Aug 2007 14:52:56.327	9 Aug 2007 15:06:22.447	806.119
55	9 Aug 2007 16:38:58.951	9 Aug 2007 16:45:50.624	411.674
56	10 Aug 2007 06:54:50.853	10 Aug 2007 07:06:31.061	700.207
57	10 Aug 2007 08:36:36.097	10 Aug 2007 08:50:57.117	861.020
58	10 Aug 2007 10:20:04.232	10 Aug 2007 10:34:49.408	885.176
59	10 Aug 2007 12:03:57.691	10 Aug 2007 12:18:43.181	885.490

60	10 Aug 2007 13:47:49.935	10 Aug 2007 14:02:01.584	851.649
61	10 Aug 2007 15:32:32.609	10 Aug 2007 15:43:17.622	645.013
62	11 Aug 2007 05:51:44.367	11 Aug 2007 06:00:34.029	529.662
63	11 Aug 2007 07:32:07.712	11 Aug 2007 07:45:53.318	825.606
64	11 Aug 2007 09:15:07.798	11 Aug 2007 09:29:49.484	881.687
65	11 Aug 2007 10:58:57.898	11 Aug 2007 11:13:43.673	885.774
66	11 Aug 2007 12:42:49.400	11 Aug 2007 12:57:23.496	874.096
67	11 Aug 2007 14:26:58.991	11 Aug 2007 14:39:41.665	762.674
68	12 Aug 2007 06:28:00.143	12 Aug 2007 06:40:39.952	759.809
69	12 Aug 2007 08:10:18.421	12 Aug 2007 08:24:49.976	871.555
70	12 Aug 2007 09:53:57.529	12 Aug 2007 10:08:42.491	884.961
71	12 Aug 2007 11:37:50.573	12 Aug 2007 11:52:33.511	882.938
72	12 Aug 2007 13:21:45.934	12 Aug 2007 13:35:33.819	827.884
73	12 Aug 2007 15:07:05.442	12 Aug 2007 15:15:56.257	530.815
74	13 Aug 2007 05:24:24.041	13 Aug 2007 05:35:06.050	642.009
75	13 Aug 2007 07:05:40.587	13 Aug 2007 07:19:48.727	848.140
76	13 Aug 2007 08:48:58.573	13 Aug 2007 09:03:41.711	883.138
77	13 Aug 2007 10:32:51.240	13 Aug 2007 10:47:36.157	884.917
78	13 Aug 2007 12:16:42.451	13 Aug 2007 12:31:04.786	862.335
79	13 Aug 2007 14:01:08.136	13 Aug 2007 14:12:49.644	701.509
80	14 Aug 2007 04:21:50.473	14 Aug 2007 04:28:39.566	409.093
81	14 Aug 2007 06:01:19.624	14 Aug 2007 06:14:41.646	802.022
82	14 Aug 2007 07:44:04.315	14 Aug 2007 07:58:41.865	877.550
83	14 Aug 2007 09:27:50.881	14 Aug 2007 09:42:35.327	884.446
84	14 Aug 2007 11:11:42.838	14 Aug 2007 11:26:20.889	878.051
85	14 Aug 2007 12:55:44.779	14 Aug 2007 13:08:58.355	793.576
86	14 Aug 2007 14:42:14.944	14 Aug 2007 14:47:54.124	339.181
87	15 Aug 2007 04:57:22.977	15 Aug 2007 05:09:21.460	718.483
88	15 Aug 2007 06:39:18.853	15 Aug 2007 06:53:41.780	862.927
89	15 Aug 2007 08:22:50.549	15 Aug 2007 08:37:33.886	883.337
90	15 Aug 2007 10:06:43.790	15 Aug 2007 10:21:27.044	883.254
91	15 Aug 2007 11:50:36.405	15 Aug 2007 12:04:40.531	844.125
92	15 Aug 2007 13:35:27.991	15 Aug 2007 13:45:42.386	614.395
93	16 Aug 2007 03:54:05.775	16 Aug 2007 04:03:32.420	566.644
94	16 Aug 2007 05:34:46.969	16 Aug 2007 05:48:38.561	831.592
95	16 Aug 2007 07:17:52.826	16 Aug 2007 07:32:33.306	880.480
96	16 Aug 2007 09:01:43.811	16 Aug 2007 09:16:27.567	883.756
97	16 Aug 2007 10:45:34.862	16 Aug 2007 11:00:04.421	869.559
98	16 Aug 2007 12:29:48.285	16 Aug 2007 12:42:13.407	745.123
99	17 Aug 2007 02:52:44.031	17 Aug 2007 02:55:57.329	193.299
100	17 Aug 2007 04:30:34.592	17 Aug 2007 04:43:27.062	772.470
101	17 Aug 2007 06:13:01.387	17 Aug 2007 06:27:33.409	872.022
102	17 Aug 2007 07:56:43.014	17 Aug 2007 08:11:25.984	882.970
103	17 Aug 2007 09:40:35.583	17 Aug 2007 09:55:15.603	880.019
104	17 Aug 2007 11:24:32.295	17 Aug 2007 11:38:09.578	817.283
105	17 Aug 2007 13:10:07.643	17 Aug 2007 13:18:11.074	483.431
106	18 Aug 2007 03:26:51.169	18 Aug 2007 03:37:57.665	666.495
107	18 Aug 2007 05:08:20.596	18 Aug 2007 05:22:32.325	851.729
108	18 Aug 2007 06:51:43.108	18 Aug 2007 07:06:24.616	881.508
109	18 Aug 2007 08:35:36.024	18 Aug 2007 08:50:18.714	882.691
110	18 Aug 2007 10:19:27.258	18 Aug 2007 10:33:43.174	855.916
111	18 Aug 2007 12:03:59.319	18 Aug 2007 12:15:16.293	676.974
112	19 Aug 2007 02:24:00.874	19 Aug 2007 02:31:45.293	464.419
113	19 Aug 2007 04:03:55.598	19 Aug 2007 04:17:26.335	810.736
114	19 Aug 2007 05:46:47.194	19 Aug 2007 06:01:24.275	877.081
115	19 Aug 2007 07:30:35.363	19 Aug 2007 07:45:17.795	882.432
116	19 Aug 2007 09:14:26.862	19 Aug 2007 09:29:00.981	874.119
117	19 Aug 2007 10:58:31.507	19 Aug 2007 11:11:30.491	778.985
118	19 Aug 2007 12:45:43.060	19 Aug 2007 12:49:40.056	236.995
119	20 Aug 2007 02:59:53.302	20 Aug 2007 03:12:08.904	735.602
120	20 Aug 2007 04:41:59.252	20 Aug 2007 04:56:24.063	864.811
121	20 Aug 2007 06:25:34.357	20 Aug 2007 06:40:15.924	881.567
122	20 Aug 2007 08:09:27.437	20 Aug 2007 08:24:08.094	880.656
123	20 Aug 2007 09:53:20.834	20 Aug 2007 10:07:16.099	835.265
124	20 Aug 2007 11:38:23.040	20 Aug 2007 11:48:02.074	579.034
125	21 Aug 2007 01:56:26.576	21 Aug 2007 02:06:26.629	600.053
126	21 Aug 2007 03:37:23.942	21 Aug 2007 03:51:21.385	837.443
127	21 Aug 2007 05:20:35.338	21 Aug 2007 05:35:14.821	879.483
128	21 Aug 2007 07:04:27.160	21 Aug 2007 07:19:08.910	881.750
129	21 Aug 2007 08:48:18.050	21 Aug 2007 09:02:42.279	864.228
130	21 Aug 2007 10:32:36.093	21 Aug 2007 10:44:41.274	725.181
131	22 Aug 2007 00:54:23.382	22 Aug 2007 00:59:30.439	307.057
132	22 Aug 2007 02:33:06.922	22 Aug 2007 02:46:11.565	784.643
133	22 Aug 2007 04:15:41.838	22 Aug 2007 04:30:14.586	872.749
134	22 Aug 2007 05:59:25.857	22 Aug 2007 06:14:07.126	881.270
135	22 Aug 2007 07:43:18.121	22 Aug 2007 07:57:54.903	876.781
136	22 Aug 2007 09:27:16.675	22 Aug 2007 09:40:41.953	805.278
137	22 Aug 2007 11:13:11.942	22 Aug 2007 11:20:18.513	426.571
138	23 Aug 2007 01:29:16.658	23 Aug 2007 01:40:46.072	689.414

139	23 Aug 2007 03:10:58.124	23 Aug 2007 03:25:13.624	855.500
140	23 Aug 2007 04:54:24.954	23 Aug 2007 05:09:05.289	880.335
141	23 Aug 2007 06:38:18.157	23 Aug 2007 06:52:58.720	880.563
142	23 Aug 2007 08:22:09.766	23 Aug 2007 08:36:18.491	848.725
143	23 Aug 2007 10:06:49.385	23 Aug 2007 10:17:38.724	649.338
144	24 Aug 2007 00:26:12.589	24 Aug 2007 00:34:44.701	512.113
145	24 Aug 2007 02:06:29.176	24 Aug 2007 02:20:08.559	819.383
146	24 Aug 2007 03:49:27.354	24 Aug 2007 04:04:04.466	877.112
147	24 Aug 2007 05:33:17.032	24 Aug 2007 05:47:57.898	880.866
148	24 Aug 2007 07:17:08.321	24 Aug 2007 07:31:38.250	869.929
149	24 Aug 2007 09:01:16.316	24 Aug 2007 09:13:59.123	762.807
150	25 Aug 2007 01:02:21.443	25 Aug 2007 01:14:53.483	752.040
151	25 Aug 2007 02:44:36.916	25 Aug 2007 02:59:04.056	867.140
152	25 Aug 2007 04:28:15.239	25 Aug 2007 04:42:55.689	880.451
153	25 Aug 2007 06:12:08.270	25 Aug 2007 06:26:46.501	878.231
154	25 Aug 2007 07:56:02.883	25 Aug 2007 08:09:48.498	825.615
155	25 Aug 2007 09:41:17.846	25 Aug 2007 09:50:16.567	538.721
156	25 Aug 2007 23:58:46.078	26 Aug 2007 00:09:16.857	630.780
157	26 Aug 2007 01:39:58.209	26 Aug 2007 01:54:01.747	843.538
158	26 Aug 2007 03:23:14.860	26 Aug 2007 03:37:54.062	879.201
159	26 Aug 2007 05:07:07.481	26 Aug 2007 05:21:47.758	880.278
160	26 Aug 2007 06:50:58.510	26 Aug 2007 07:05:17.185	858.675
161	26 Aug 2007 08:35:22.068	26 Aug 2007 08:47:05.335	703.267
162	26 Aug 2007 22:56:17.338	26 Aug 2007 23:02:43.411	386.073
163	27 Aug 2007 00:35:36.645	27 Aug 2007 00:48:53.281	796.636
164	27 Aug 2007 02:18:19.267	27 Aug 2007 02:32:53.406	874.139
165	27 Aug 2007 04:02:05.515	27 Aug 2007 04:16:45.859	880.344
166	27 Aug 2007 05:45:57.632	27 Aug 2007 06:00:31.426	873.794
167	27 Aug 2007 07:29:58.589	27 Aug 2007 07:43:10.972	792.382
168	27 Aug 2007 09:16:19.872	27 Aug 2007 09:22:16.642	356.770
169	27 Aug 2007 23:31:39.939	27 Aug 2007 23:43:31.083	711.144
170	28 Aug 2007 01:13:32.636	28 Aug 2007 01:27:52.403	859.767
171	28 Aug 2007 02:57:03.528	28 Aug 2007 03:11:43.568	880.040
172	28 Aug 2007 04:40:57.029	28 Aug 2007 04:55:36.089	879.060
173	28 Aug 2007 06:24:49.397	28 Aug 2007 06:38:50.708	841.311
174	28 Aug 2007 08:09:37.918	28 Aug 2007 08:19:56.810	618.892
175	28 Aug 2007 22:28:24.116	28 Aug 2007 22:37:38.469	554.352
176	29 Aug 2007 00:08:59.827	29 Aug 2007 00:22:48.016	828.189
177	29 Aug 2007 01:52:04.214	29 Aug 2007 02:06:42.216	878.001
178	29 Aug 2007 03:35:55.291	29 Aug 2007 03:50:35.457	880.166
179	29 Aug 2007 05:19:46.581	29 Aug 2007 05:34:12.607	866.026
180	29 Aug 2007 07:03:58.618	29 Aug 2007 07:16:24.190	745.572
181	29 Aug 2007 21:27:23.888	29 Aug 2007 21:29:39.507	135.619
182	29 Aug 2007 23:04:46.916	29 Aug 2007 23:17:34.883	767.966
183	30 Aug 2007 00:47:11.336	30 Aug 2007 01:01:41.481	870.145
184	30 Aug 2007 02:30:52.634	30 Aug 2007 02:45:32.962	880.327
185	30 Aug 2007 04:14:45.683	30 Aug 2007 04:29:22.162	876.479
186	30 Aug 2007 05:58:41.962	30 Aug 2007 06:12:17.680	815.718
187	30 Aug 2007 07:44:12.241	30 Aug 2007 07:52:25.416	493.176
188	30 Aug 2007 22:01:03.714	30 Aug 2007 22:12:02.955	659.242
189	30 Aug 2007 23:42:29.336	30 Aug 2007 23:56:39.337	850.001
190	31 Aug 2007 01:25:50.896	31 Aug 2007 01:40:30.797	879.901
191	31 Aug 2007 03:09:44.238	31 Aug 2007 03:24:23.977	879.739
192	31 Aug 2007 04:53:35.684	31 Aug 2007 05:07:49.097	853.414
193	31 Aug 2007 06:38:05.671	31 Aug 2007 06:49:25.584	679.914
194	31 Aug 2007 20:58:16.265	31 Aug 2007 21:05:45.263	448.998
195	31 Aug 2007 22:38:03.449	31 Aug 2007 22:51:31.904	808.454
196	1 Sep 2007 00:20:53.272	1 Sep 2007 00:35:29.615	876.343
197	1 Sep 2007 02:04:41.537	1 Sep 2007 02:19:22.013	880.476
198	1 Sep 2007 03:48:33.620	1 Sep 2007 04:03:05.092	871.472
199	1 Sep 2007 05:32:37.507	1 Sep 2007 05:45:36.663	779.156
200	1 Sep 2007 07:19:35.351	1 Sep 2007 07:24:01.078	265.727

Global Statistics

Min Duration	181	29 Aug 2007 21:27:23.888	29 Aug 2007 21:29:39.507	135.619
Max Duration	14	3 Aug 2007 14:27:14.558	3 Aug 2007 14:42:02.079	887.521
Mean Duration				765.692
Total Duration				153138.435

Bibliography

[1] Robert D, Lt Col Newberry, "Powered Spaceflight for Responsive Space Systems," *High Frontier*, vol. 1, no. 4, pp. 46-49, 2005.

[2] James R Wertz, Ed., *Space Mission Analysis and Design*, 3rd ed. El Segundo, United States of America: Microcosm Press, 1999.

[3] Christophe R. Koppel, Oliver Duchemin, and Dominique Valentian, "High Power Electric Propulsion System for NEP: Propulsion and Trajectory Options," in *Space Technology and Applications International Forum*, 2006, pp. 484-493.

[4] John W. Dankanich and Tara Polsgrove, "Mission Benefits of Gridded Ion and Hall Thruster Hybrid Propulsion Systems," in *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Sacramento, 2006, pp. 1-11.

[5] Thomas M. Randolph, "Qualification of Commercial Electric Propulsion Systems for Deep Space Missions," in *30th International Electric Propulsion Conference*, Florence, 2007, pp. 1-16.

[6] Y Raitses, T Moeller, and J Szabo, "AEDC Plume Measurements Using Bi-Directional Ion Flux Probes," in *30th International Electric Propulsion Conference*, Florence, 2007.

[7] Inc Busek Co. (2008) Busek Space Propulsion. [Online]. http://www.busek.com/downloads/HighPower.pdf

[8] Inc Busek Co. (2008) Busek Space Propulsion. [Online]. http://www.busek.com/downloads/BrochureDesign-LowPower-v2.pdf

[9] David Y. Oh, "Evaluation of Solar Electric Propulsion Technologies for Discovery-Class Missions," *Journal of Spacecraft and Rockets*, vol. 44, no. 2, pp. 399-411, March-April 2007.

[10] Daniel A Herman and George C Soulas, "Status of the NEXT Ion Thruster Long-Duration Test after 10,100 h and 207 kG Demonstrated," in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Cincinnati, 2007, pp. 1-35.

[11] Roger Walker et al., "Initial Experiments on a Dual-Stage 4-Grid Ion Thruster for Very High Specific Impulse and Power," in *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Sacramento, 2006, pp. 1-11.

[12] John W, Jr Dunning, Scott Benson, and Steven Oleson, "NASA's Electric Propulsion Program," in *27th International Electric Propulsion Conference*, Pasadena, 2001,

pp. 1-12.

[13] Paola Rossetti, Massimo Saverdi, and Leonardo Biagioni, "Electric-Propulsion Systems," in *Advanced Propulsion Systems and Technologies, Today to 2020*, Frank K. Lu, Ed. Reston, United States of America: American Institute of Aeronautics and Astronautics, 2008, ch. 10, pp. 223-289.

[14] John W Dankanich and Gordon R Woodcock, "Electric Propulsion Performance from Geo-transfer to Geosynchronous Orbits," in *30th International Electric Propulsion Conference*, Florence, 2007, pp. 1-10.

[15] David C Byers and John W Dankanich, "Geosynchronous-Earth-Orbit Communication Satellite Deliveries with Integrated Electric Propulsion," *Journal of Propulsion and Power*, vol. 24, no. 6, pp. 1369-1375, November-December 2008.

[16] C S Welch, "Ascending Node Alteration of Polar Orbiting Spacecraft Using Low-thrust Propulsion," *Proc Inst Mech Engrs*, vol. 214, pp. 313-321, September 2000.

[17] Michael A. Mesarch, "Orbit Optimization for the Geospace Electrodynamics Connections (GEC) Mission," in *AIAA/AAS Astrodynamics Conference*, Providence, 2004, pp. 1-13.

[18] William E Wiesel, *Spaceflight Dynamics*, 2nd ed. New York, Unite States of America: McGraw-Hill, 1997.

[19] National Aeronautics and Space Administration. (2007, Feb) Glossary of Terms. [Online]. http://asd-www.larc.nasa.gov/Instrument/glossary/k.html

Vita

Captain Timothy S. Hall graduated from Socorro High School in Socorro, New Mexico. He entered undergraduate studies at New Mexico State University in Las Cruces, New Mexico where he graduated with a Bachelor of Science degree in Agriculture in May 1997. He enlisted in the Air Force in 1998 and spent 3 years as a KC-10 maintainer. In 2001, he was commissioned through Officer Training School.

His first assignment was at Vandenberg AFB as a student in the Minuteman III ICBM Initial Qualification Training Program. In 2002, he was assigned to the 319th Missile Squadron, F.E. Warren AFB, Wyoming where he served as an ICBM Missile Combat Crew Member. While at F.E. Warren, he also served as the Senior Combat Crew Commander Evaluator for the 90th Operations Group, the Chief of the ICBM Weapons and Tactics Flight Targeting section in the 90th Operations Support Squadron, and the Chief of Combat Crew Procedures for the 20th Air Force Weapons and Tactics Section.

In June 2008, Captain Hall was awarded a Masters of Strategic Intelligence degree from American Military University in Manassas, West Virginia. In August 2008, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to Global Strike Command at Barksdale AFB, LA.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
25-03-2010	Master's Thesis	Sep 2008 - Mar 2010

TITLE AND SUBTITLE Orbit Maneuver For Responsive Coverage Using Electric Propulsion	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
AUTHOR(S) Hall, Timothy S., Captain, USAF	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Street, Building 642 WPAFB OH 45433-7765	8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GSS/ENY/10-M04
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Undisclosed Sponsor	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The use of continuous electric propulsion to manipulate a satellite's orbit offers significant potential for enhancing coverage of a target in ways not previously considered. Elliptical orbits utilizing a very low perigee can facilitate access to the surface and atmosphere of the Earth at sub-ionosphere altitudes while counteracting atmospheric drag forces using continuous electric propulsion. Additionally, in-plane and out-of-plane manipulation of both circular and elliptical orbits can allow for passage of a satellite over a target at a given time.

Sustained low perigee orbit was modeled with an initial perigee altitude of 100 km and various apogee altitudes to derive a range of apogee altitudes that could sustain the orbit. Operation was demonstrated for current as well as future thruster capabilities.

To evaluate opportunities for a scheduled access, circular and various elliptical orbits were modeled using continuous thrust. It was found that electric propulsion was capable of improving potential temporal access of a target to 30% for circular orbits and nearly 70% for elliptical orbits

Recommendations include further modeling of low perigee orbits and the effects of atmospheric variation at solar extremes on mission lifetime. Derivation of optimal thrust duration and angle could greatly enhance the performance of the thruster and warrants continued research. Finally, the use of responsive maneuver operationally will require development of a scheduling algorithm to plan passage over a given target at a given time.

15. SUBJECT TERMS
low perigee; operationally responsive space; continuous thrust maneuver; continuous electric propulsion; sub-ionospheric orbit

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Dr. Richard G. Cobb, AFIT/ENY
REPORT U	ABSTRACT U	c. THIS PAGE U	UU	99	19b. TELEPHONE NUMBER *(Include area code)* (937) 255-3636, ext 4559; e-mail: Richard.Cobb@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18